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SIGNAL CORPS CENTENNIAL ISSUE

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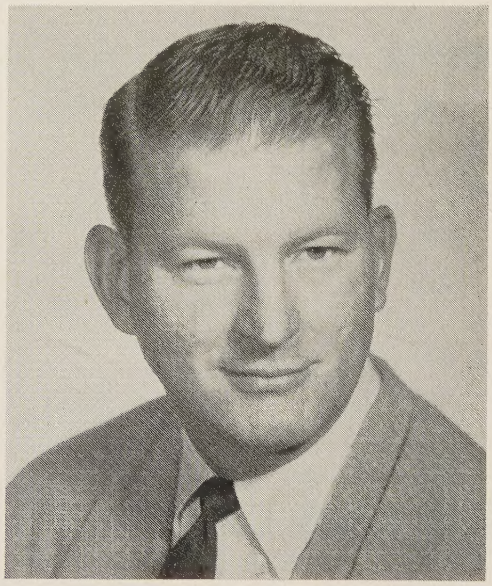
SIGNAL CORPS CENTENNIAL ISSUE

In Memorium



James Q. Brantley, Jr.

Dr. James Q. Brantley, Jr. (S'48–A'53–SM'56), Coeditor of the IRE TRANSACTIONS ON MILITARY ELECTRONICS and a charter member of the IRE-PGMIL Administrative Committee, died of cancer on September 14, 1960, at the age of 33. He was Vice President for Research and Director of the Research Division of Radiation Incorporated in Orlando, Fla., a position he had held since 1959. Prior to his appointment as Vice President he had formed and was director of the Research Division, coming to Radiation Incorporated from the Cornell Aeronautical Laboratory of Cornell University, Ithaca, N. Y., in 1957.

Dr. Brantley joined CAL in 1952 after receiving his doctorate. He did his undergraduate work at the University of Florida, Gainesville, where he earned the B.E.E. degree in 1949 on a Tuft's Memorial Scholarship, following a 20-month tour of duty with the Navy in 1945–1946. For three years he was the recipient of a CAL Fellowship in Electrical Engineering on which he obtained the M.E.E. degree in 1950 and the Ph.D. degree in electrical engineering in 1952. The CAL Fellowship's stipulation that "the recipient do work beneficial to the aviation industry" led to his investigation of the aircraft collision problem, sponsored jointly by the Cornell School of Electrical Engineering (Ithaca) and CAL in Buffalo.

At CAL he was a member of the technical staff of Project Buffalo Bill, a laboratory wide project for the Tactical Air Command. He originated and led the CAL program in terrain avoidance, and his research into uses of Doppler radar led him to the development of the first tornado warning radar to operate on the principle that internal turbulence may be identified by its Doppler spectrum.

At Radiation Incorporated he led the corporate effort and obtained government sponsorship in a number of new research programs, in such diverse areas as interplanetary navigation, satellite attitude and position sensing, tactical air-to-surface missile systems, the Van Allen radiation belts, and the U. S. postal system.

Dr. Brantley was past chairman of the Orlando Section of the American Rocket Society and of the IRE-PGMIL, past vice chairman of the Central Florida Section of the IRE, and a past member of the Radio Technical Commission for Aeronautics, Special Committee 74. He was a member of Sigma Xi, the Institute of Aeronautical Sciences, and the American Rocket Society, and a Fellow of the British Interplanetary Society.

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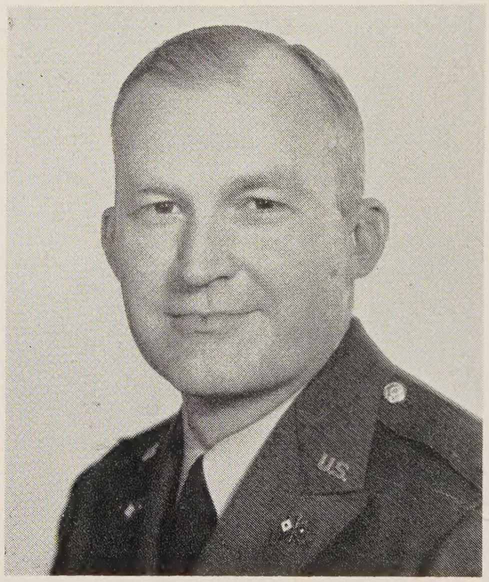

Harold McD. Brown

Colonel Harold McD. Brown (SM'57), Commanding Officer of USASRDL, Fort Monmouth, N. J., was born in Macon, Ga., on March 13, 1916. He entered the U. S. Military Academy at West Point in 1933 and was commissioned a second lieutenant in the Infantry at his graduation in 1937. After graduation from the Signal School in 1940, he transferred to the Signal Corps. He also attended the Command and General Staff School, the Armed Forces Staff College, and the Army War College.

Colonel Brown has served in several locations within the continental United States, including assignments within the Office of the Chief Signal Officer, and the staff of the Department of Defense. During World War II he served in the European Theater where he commanded the 61st Signal Battalion (Corps). He has been awarded the Legion of Merit and the Army Commendation Ribbon with Medal Pendant.

He has been Commanding Officer at USASRDL since 1958.

One Hundred Years of Service

THIS issue of the IRE TRANSACTIONS ON MILITARY ELECTRONICS is devoted entirely to the U. S. Army Signal Corps in recognition of its centennial anniversary of service to the nation. Selected articles within these pages will give the reader an appreciation of some of the Corps' brilliant history as well as its approach to the solution of current scientific problems.

This centennial anniversary brackets a hundred-year segment of colorful and fast-moving military history. It has been a period of singular extensions of science as applied to the battlefield. Notable among them have been advances in all three essential elements of military operations: firepower, mobility, and communications.

The history of progress in military electronics has been a history of cooperative enterprise. In a series of instances, advances by industry have applied directly to the battlefield; in others, military need has sparked creative invention that led to wholly new products in industry. Throughout the century, the progress of one has extended the progress of the other. Today, such joint effort, spanning all aspects of technology, lies at the base of our national military strength.

While the Army Signal Corps' 100th anniversary marks a past period of progress, it also marks the entrance of the Corps into a future of far greater challenge. This future begins in an era when a single advance in technology is exerting more impact on military science than any other event in the history of warfare—the development and control of nuclear reactions that can readily be applied to battlefield weapons. Their impact on tactics, and in turn upon the sciences fitted to their support, is far-reaching, especially in communications-electronics. We see versatile nuclear weapons capable of dominating the battlefield of the future and introducing the greatest firepower increase in history, yet requiring a proportionate increase in mobility for ground combat. As a result of the advances in missile science, we have a new artillery capable of unprecedented destruction at great ranges, with both sides in combat being capable of massive blows delivered with great flexibility.

Preparedness in the nuclear field, however, does not necessarily forecast that all engagements of the future will see the use of these weapons. Indeed, many types of military operations may be conducted without them. The decisions as to these matters will be made at the highest levels and will be based on national objectives and national policy for the particular case in hand. The preparation for possible future combat, therefore, demands development of a state of readiness covering a wide variety of situations and circumstances.

Fitted to such varying tactical situations are the Army's new organizational concepts which are keyed to the application of graduated force, and have the dual capability for conventional combat, or for hard-hitting application of nuclear weapons. But their proper functioning in combat presents one of the greatest communications-electronics challenges in history. Consider the necessarily wide dispersal of troops of both sides on the battlefield. When a situation arises that can be exploited, commanders must not only get the facts quickly, and often from a distance, as the situation develops, but must be able to process and disseminate their decisions to all elements in a timely fashion. A rapid and reliable battlefield-information process, together with fast and precise command control over units widely dispersed across the combat area, are indispensable partners to future success in ground combat.

Among the key scientific systems needed for the modern army, therefore, is one of combat area surveillance for information on enemy movement and for the location of timely targets this movement presents. Its system concepts and indeed the development of many of its components are well under way, spanning an array of sensory means including radar, infrared, photographic, visual, acoustic, seismic, radiometric and meteorological devices.

Army communications systems serving the dual needs of conventional or nuclear combat emphasize three characteristics to a greater degree than in the past: they must provide a greatly increased communications capacity per military unit; they must span greater distances; and they must possess a high degree of systems interconnectivity.

To support these greater communications-electronics needs, all of us must probe into extended uses of the science, for example, into space vehicles for communications and combat surveillance purposes, messenger drones as ground-directed relay points, and even into the creation of artificial ionospheres as short-time conveyors of military intelligence. Added to these are perhaps a dozen more approaches toward an increase in communications capacity. As history repeats, their solution will come through the joint imagination and teamwork of industrial and service laboratories; and again this solution will both strengthen the national security, and pay substantial dividends through civilian application to the nation as a whole.

The Army Signal Corps joins with its colleagues of the IRE, industry, and the other military services in attacking the scientific problems of military electronics. It is the Corps' proud hope that its second century of existence will provide even greater opportunities for service to the nation.

COL. HAROLD McD. BROWN, *Guest Editor*

One Hundred Years of Research*

HAROLD A. ZAHL†, FELLOW, IRE

Summary—On June 21, 1960, the U. S. Army Signal Corps celebrated its 100th birthday—a century of service to the Army and the Nation.

In the narrative which follows, particular attention is directed toward a few selected items of research which characterize the scientific past and present of the Corps; it is concluded by a look toward the future.

Stressed are the facts that, over the years, signal research has had a profound effect on the nation's military posture, that this is of importance in periods of wartime stress, and finally, that the peacetime economy has also gained, both directly and indirectly, from much of this research. The article also includes a short summary of the Greely mission to the Arctic covering the period of 1881–1884—the tragedies of the expedition, and its scientific achievements.

Looking ahead, the narrative concludes with a brief description of signal research in several areas which today show great promise as the nation moves forward into the unknown of tomorrow.

At 4:00 A.M. on Sunday, December 7, 1941, two U. S. Army signalmen, Lockard and Elliott, switched on their radar for a routine 3-hour run at their station in Oahu. Their orders were to keep the equipment on the air until 7:00 A.M., when a truck was to pick them up and return them to barracks.

But a new chapter of history was in the making, and contributing to the introduction was the fact that their transportation was late in arriving. So, to gain more practice with their new aircraft detection equipment, they kept it running overtime. Suddenly at 7:02 their TV-like cathode-ray tube (on which small bright spots meant airplanes) developed a dim cloud, the like of which they had never seen before. The cloud grew brighter with time and, as the fateful seconds ticked off, seemed to be coming closer. Their first reaction was—equipment failure—and so they hurriedly made a check, but all was well, the meters read correctly, and the power unit outside droned on monotonously.

Now excited, they made some quick calculations and decided that this massive echo really represented a flight of unidentified airplanes 132 miles off Kahuku Point approaching at 180 miles per hour, a fact which they formally reported by telephone at 7:20 A.M.

The first bombs fell at 7:55 A.M. . . .

Though the bombing of Pearl Harbor is a dismal part of over-all U.S. history, a small group of scientists and engineers at Fort Monmouth, N. J., on learning that their equipment at least had functioned, felt tremendous personal relief coupled with a certain type of grim technical satisfaction. The responsibility for what was done with these historic data had not been theirs. However, had the radar been operating and ineffectual, no one in that small early-morning aspirin-chewing group on the following day doubted for one moment that part of the arrow of blame would have pointed in their direction, and with some justification, since the entire concept of early-warning radar was to prevent just such surprise attacks.

Almost 20 years later, and in peace, at Kaena Point, in our now fiftieth state, another historic observation was made, an observation which also was announced to the world by the President of the United States. This time it was not the belated news of an enemy invasion—it was TIROS, and the invaders were friendly clouds and weather fronts.

History again, for under Signal Corps technical direction, and as a part of the National Aeronautics and Space Administration program, the earth had acquired a new moon on April 1, 1960. Powered by the sun's rays, it radioed back TV-like pictures of the earth's weather. These pictures will also be long remembered, but this time for man's eternal glory and benefit—and not "in infamy" as President Roosevelt bitterly predicted in speaking of the 1941 holocaust.

These two events, so close together in geography, but widely separated in time, seem admirably suited to introduce the story of the Centennial Anniversary of the U. S. Army Signal Corps, serving its country in war and in peace. The combat aspects of this proud Corps shine brightly in the annals of our military history; but in research and development, not only is there a long record of militarily impressive contributions to our defense, but there also comes strong satisfaction in the realization that many of the by-products of this military-supported research, started by General A. J. Myer (Fig, 1) in 1860, serve to enrich everyone's living in peace.

It was signal research during and after the Civil War which provided this country with its first weather service, a service decades later recognized as being so indispensable that in 1890 Congress established the U. S. Weather Bureau under the Department of Agriculture, using the Army Weather Service nuclei as building blocks upon which to construct the new civilian operation.

It was signal research which gave the first government support to aviation when it bought an airplane from the Wright brothers in 1908 and quickly expanded this interest to include surveillance techniques, machine guns, bombs, and bombsights. With people like the late General G. O. Squier and Nobel Prize-winning physicist, R. A. Millikan (also a World War I Signal Officer), aviation interest expanded, growing into maturity so rapidly that near the end of World War I, the Army Air Corps was formed and "crossed-flags" were routinely exchanged for "wings."

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

In electronics, research aimed at winning this same war brought about radio broadcasting as we have long enjoyed it, at least ten years before normal peacetime practices would have made it available to the public. In fact, radio was so new in World War I that when the Germans cut all his telephone wires, one U. S. commander doubtingly radioed back to his headquarters, "I am entirely out of communications."

It was radar, now indispensable to all aviation, which also did so much to make the cathode-ray tube commercially practical as the picture screen of present-day television, while the sensitivity of our present-day TV cameras can be traced back, in part, to the late war days when "shot-up" bombers, good only for one last flight, were loaded with high explosives and, unmanned, flown through heavy flak into choice enemy targets where they were deliberately crashed with tremendous devastation—TV eyes and research substituting for the dreaded kamikaze in which the pilot also flew a terminal mission.

Over the years, in much of its research, the Signal Corps has received generous support from American industry and educational institutions. Almost every electronic industry, its photographic and meteorological counterparts, parts of the aviation complex, and over 100 colleges and universities—all are a part of the story being told the force behind Signal research.

A poet might well see this force as an ethereal substance which hides behind every cloud and weather front . . . in daring men as they communicate with each other in combat . . . in an aviator who looks about wondering how he got where he is, what is his mission, how to do it, and if possible how to get home . . . in radar reaching out as far as the moon and beyond . . . in the confidence good communications instills in a commander and his troops . . . in the eyes and the ears of intelligence . . . in an artificial earth satellite seeing from afar and passing its electrical sensing back to earth. Through the microscope of a scientist, it may even be the atom waiting to give up its secrets to men wise enough to probe deeply and with understanding.

The many individuals and diversified groups involved naturally see this century-old drama differently (like the mixed reactions of an audience to a piece of modern art), for, in the fury of war, the immediate environment and one's emotions make broad perspective difficult to realize. But one aspect all see alike; a living vibrant force which erupts violently when our nation's security is threatened. And as millions who have fought for their country surely sensed, in war this force became military communications and combat surveillance, without which victory would have been impossible.

Fig. 1.

The present center of this research is at Fort Monmouth, N. J., where the USASRDL three thousand top-notch scientists, engineers, supporting personnel, and a carefully selected military cadre peer into the crystal ball of science—and as they see, the nation's defense continuously grows stronger. Much of their recent vi-

sion, understandably, must be kept in secrecy, but as the new becomes routine, the curtains of secrecy lift.

The early history of radar was particularly exciting. Everything thought of, everything done, was an important invention or demonstration thereof, for the field was new. Almost each test, too, brought in the unexpected; for example, in the 1938 experiments at Fort Monroe, Va., a bomber pilot assisting in tests was unknowingly blown to sea in the upper altitude torrent of the then unknown jet streams, and radar brought the crew back to safety. And on the west coast, early in radar's history, there was the case of the daring civilian pilot who took off in a small airplane from Nevada flying to California; when faced with landing, he found pea soup fog embracing his entire gasoline potential. With minutes of air time left and without a parachute, good luck stepped in, and he made radio contact with a scientist at an experimental Signal Corps blind-landing device, whose calm voice broke through the visually impenetrable fog and said, "Do exactly as I say and I'll bring you in." The pilot complied, his choice being rather limited! And soon there appeared a landing field a few feet below the airplane, and all was well. But the miracle-producing device was still secret, and so the lucky pilot, while extremely grateful, was denied the answer to his question as to how his stay on earth had been magically prolonged. But not so today, for all aviation now uses blind-landing techniques routinely.

In World War II, with the superb NDRC Laboratories in the vanguard, came microwave fire control radar which cleared the air of the dreaded buzz bomb; there came also blind bombing which accurately rained death through protective clouds, super navigation, the proximity fuze which contributed so greatly to the defeat of the kamikaze, electronic countermeasures, and myriads of inventions which wartime wrath and ingenuity devised.

With everyone helping now, much of the effort of Signal Corps Laboratories went toward coordination responsibilities, "crash developments," routine equipment testing, specifications, contracts, delivery, operability, and maintenance—often involving tests under grueling combat conditions. Purple Hearts were common to those whose ammunition was electrons instead of bullets. At Monmouth alone, a peak civilian personnel force of 14,800 was reached in 1943. At Wright Field, many additional thousands of Signal Corps personnel carried on similar tasks related to Army Air Corps activities.

But with all the assistance total mobilization brought, there were many problem areas where the most learned hesitated to travel, lest the war be over before the problem could be solved—if it could be solved at all. Riding high in this category was the location of enemy mortars, the deadly device which caused the majority of our ground casualties.

The problem was one of finding metal objects the size of a small tomato can, loaded with explosives and fired at our troops in bursts of hundreds, with nothing more complicated than an augmented shot-gun shell at the bottom of a piece of iron pipe. Finding these clouds of hell-created torpedo raindrops coming unannounced toward one from miles away was the first part of the problem; the next was to establish definitive trajectories, trace the various shell paths back to their points of origin, and by coincidence methods, to saturate these coordinates with overwhelming counterfire so that peace and quiet would again prevail in those particular areas—and many thousands like them!

With Major General R. B. Colton challenging his scientists and engineers, signal research took on this problem during the war when much talented advice said there was no quick solution. A field laboratory in Paris and scientists at Monmouth concurrently struck hard. At Monmouth, they even took advantage of the small size of the target and picked a radar wavelength which made these tiny lethal projectiles fairly glisten in the glow of the radar's illumination. Within six months the problem was solved, and to hurry the first equipments into emergency overseas air freight, a task force of 20 signal research men (and one woman) worked 96 consecutive hours; and a tired, sleepy, and bearded (one exception) crew of scientists and engineers on the verge of collapse cheered as the first equipments were loaded for flight into Pacific combat areas. They had done it—and had well earned the long sleep which soon engulfed them.

Immediately after the war, the country's most powerful radar, DIANA, was retuned for peaceful intercepts. In January, 1946, at Fort Monmouth, in return for eons of its own beautiful glow, the moon was caressed with earth-made radiation and seconds later the crown jewel of the sky responded with echoes which were detected at our transmitter site—in effect heralding the arrival of the Space Age.

And then came the day in 1958 when the Corps basked in pleasant and much-earned publicity, when early Laboratory Director Colonel W. R. Blair was granted the basic U. S. patent in radar for work done in the Signal Corps Laboratory prior to World War II.

Going back again in time, while radar men were excitingly opening up an entirely new field, pre-World War II communications people, with sabers now rattling in Europe, found themselves completely out of date, as U. S. tanks and airplanes were about to be expanded 100-fold in number, not to mention increased speed or mission complexity. In armor, for instance, all experience had been with AM (still the work-horse of our present civilian broadcasting system). But to produce a communications net using this system of voice modulation, and still to be superior against such noted fighters as General Rommel with his highly mobile and enormous striking power, was considered well-nigh impossible.

With a bold stroke of imagination and much-hurried research, a wise and brave decision was made to convert our system to FM, a much-neglected concept of a famed World War I Signal Officer, the late Major Armstrong. With this decision made, however, and with real dollars now backing the concept, communications soon became possible between all the many thousands of our tanks plus the supporting infantry and aircraft, which later made up General Patton's overwhelming force. And to allow for combat success, as one chased the enemy deep into Western Europe, the radio relay (now so common in our coast-to-coast TV) was quickly introduced, and U. S. armor defeated vaunted German steel with communications playing a decisive role.

In the nuclear environment, from Bikini in 1946, down the long road of atomic bomb tests to the present moratorium, we see Signal Corps scientists making experiments of civilian interest and military necessity, such as tracking atomic clouds loaded with death-dealing radioactive particles and producing dosimeters which tell how much radiation the wearer has received —whether he can be immediately returned to combat, whether he should be treated, or, more gruesomely, whether treatment would be of academic interest only.

In the same area of the atom, riding almost out of the world of fantasy, we see a strange unmanned radio-controlled weasel equipped with television eyes stalking around the deadly debris of Frenchman's Flat minutes after an atomic explosion, on command scooping up highly radioactive soil, and then rushing back to safe areas where scientists take the samples and hurriedly pass them through chemical analysis to learn more of man's assault on nature's age-old elemental stability.

For atmospheric research, our scientists set up Project Cirrus, and soon were pushing clouds around, making it rain, making it snow, causing it to clear, forming clouds—all these, of course, under selected and highly accommodating conditions, but still pointing to things to come in the future when man has applied enough patience, scientific brilliance, and hard work toward the conquest of the forces of nature. And as already mentioned, then came TIROS and its 270 pounds of sophisticated electronics thrown into orbit for us by the USAF. Tens of thousands of global cloud pictures are now available for the meteorologist to study and theorize upon, and when he is ready, to use such data in his weather predictions.

Closer to the earth, radar returns now are of immediate interest to the farmer, the Eastern Parade belle, and the millions who want to know how to plan for a sunny afternoon at the beach. Following years of research, new radar equipment was tested which observed a rainstorm 185 miles from Fort Monmouth, a storm which was tracked to range zero giving accurate precipitation forecasts for intervening areas down to the closest minute—then a bit unusual, but now commonplace. This equipment, or modifications thereof, is now in wide use in the military services and the U. S. Weather Bureau.

In recent years, one of the brightest parts of the Signal Corps unclassified research program came about when many of our scientists turned gypsy, packed their bags, and strolled down the Romany Road of the International Geophysical Year—to the Antarctic, the Arctic, the South Pacific, Western Europe, Australia, Japan, Canada, and you name it, including the USSR.

Rocket soundings producing new atmospheric data were made almost daily in various parts of the world; electromagnetic propagation data were obtained through fantastically pure ice formations in both polar regions; at Thule, a weasel equipped with an odd down-looking radar, while in rapid motion, measured ice thicknesses instantly, as compared to the weeks required by normal seismic techniques in obtaining ground contours hidden by miles of snow and ice accumulated over centuries.

Still part of the IGY: on the satellite front, our components first explored outer space with U. S. Army Ordnance Explorer I, while in Navy Vanguard I, a most exciting experiment using sun power was first tried. Launched March 17, 1958, the original solar cells still power the radio; the clear signals today give no indication of letting up, and the estimated orbit time is over 200 years. Our very first weather satellite was placed in orbit early in 1959; and while its orbital life will exceed 100 years, its electronic life is over. Its contributions, however, live on through TIROS and kindreds to come.

Viewing Signal Corps aspects of the recently completed and highly successful International Geophysical Year in retrospect, one cannot help recall the International Polar Year of 1882–1883. Congress had passed a resolution in 1879 approving this country's participation in the Arctic Project in cooperation with eleven other nations. The task of manning two U. S. stations fell to the Signal Corps with Lieutenant P. H. Ray named for Point Barrow and Lieutenant A. W. Greely assigned to Lady Franklin Bay, just 500 miles from the North Pole.

Ray's mission was outstandingly successful from all points of view and, with the country's cheers, he returned in October, 1883, showing tremendous research accomplishments; not one man of his expedition had suffered injury or been sick for even a day.

But not so with Greely . . .

Proudly marching in 1881, 1st Lt. Greely's carefully picked staff consisted of two Second Lieutenants of Infantry, one assistant surgeon, five sergeants of the Signal Corps, fourteen noncommissioned officers and men assigned from the combat arms—and two Eskimo guides.

Six came back!

Here are a few extracts from a draft copy of "Traditions of the Signal Corps," April, 1959:

On August 9, 1883, Greely broke camp . . . and with his whole party started south . . . over a drifting ice pack they labored through violent blizzards and sub-zero temperatures for twelve hours a day. Little by little they discarded everything they could except the instruments and the records . . .

Months of almost unbelievable hardships passed.

On 18 February 1884, Sgt. Cross died. He was an Infantry soldier, and the first of Greely's command to perish.

Others died.

Toward the close of April, Jens was drowned while pursuing the carcass of a shot-down bird. Nineteen men remained alive . . .

In the next five days, four men died. Fifteen were still alive . . .

On 5 June, Private Henry was executed for stealing food. Fourteen were left.

Agonizing days went on. The men were eating lichens and the oil-tanned seal-skins covers of their sleeping bags. Nobody noticed any longer who died or when. Roll-call on 21 June showed seven to be alive . . .

Above the storm one of the men thought he heard the blast of a steamship's whistle . . .

Reasoning slowly, groggily, Long decided it must be a ship. . . .

With a terrific effort he got to his feet and waved. He was too weak to shout. He started forward, collapsed and pitched headfirst down the rock, almost to the water's edge. He was picked up by sailors of the United States Navy rescue mission—

And so, of the twenty-five men who had formed the garrison of Fort Conger in the summer of 1881, six men were brought back alive in the summer of 1884! . . .

They brought back all their records. These were America's chief contribution to the international effort to discover the basic mystery of the weather. They were, in fact, among the best scientific records history had ever known. They formed an unbroken series of hourly meteorological, tidal, magnetic and pendulum observations covering a period of two full years . . .

And Researcher Lieutenant Greely lived on to become General Greely—Chief Signal Officer of the Corps which is now accepting accolades from the nation after one hundred years of service.

Before leaving Greely and his tragic experiences up north, one interestingly notes on a parallel vein that the Signal Corps' present polar veteran, Amory (Bud) Waite, in more modern times, has already made eight trips to the Antarctic, during the first of which he was one of an intrepid group of three who braved nature's most violent forces, and in the darkness of the long Antarctic night, pushed forward against great odds, and saved Admiral Byrd's life as he lay "ALONE," weak and helpless, after an all-winter vigil in the world's most desolate and isolated spot.

In closing this historic review, and in dedication to recent Chief Signal Officer, Lieutenant General J. D. O'Connell (Ret.) and present Chief, Major General R. T. Nelson, let us take a quick look at some futuristic communications. We see an experimental communication circuit between Monmouth, the moon, and the University of Illinois—a short thousand terrestrial miles also coupled magically for research through a path one-half million miles long. Or again, with tremendous electrical discharges, the environment of an exploding atomic bomb is created in the "test tube" of our laboratory in order to study possible effects that a nuclear war might have on present global radio communications. And in a related field experiment when actual atomic bombs, before the moratorium, were exploded at high altitudes in the South Atlantic, our scientists discovered two new duct-like mechanisms for propagation of waves called "hydromagnetic." These waves appeared to develop when the atomic blast completely annihilated the earth's magnetic field at that point and thus were generated as the magnetic balance re-established itself. They travel at several thousand miles per second in a layer of plasma about 1500 miles high, spreading around the earth like ripples in a magnetic pond.

In miniaturization, we see complete operating radios the size of a few lumps of sugar being assembled in the helmets of our soldiers for command control purposes. With miniaturization techniques, now far extended, also came delivery of Mobidic, the fighter-field computer which "talks faster, reacts faster," than any General (even with a Ph.D. entourage). Time alone will tell how MAN and MACHINE will divide the decision process. The machine suggests a vast area of untapped potential, but we must learn more of its language before we can even start to use efficiently the millions of small components now available leading toward ability almost to think—tomorrow, perhaps even to reason. As part of this scientific crescendo, a high-performance U. S. Army Signal Corps turbo-jet surveillance drone made its first flight in May, 1960, when, unmanned, it streaked high over Arizona terrain sending back information at the speed of light, following which it was directed to its recovery area and commanded to parachute to earth.

Finally, the Signal Corps envisages maximum use of satellites in extending its global communications. These satellites may be balloon type which spray incident radiation to any number of receivers on earth, or they may carry their own transmitter powered by solar energy and, with directional antennas, relay signals received from earth to preselected sites on this bit of cosmic dust called Earth—or perhaps elsewhere. Global communications could even be by reflections from a Saturn-like belt of chaff in orbit around the entire earth.

The first[1] demonstration of one of these concepts is already history, since on December 18, 1958, the Army Signal Corps operated a communications center in outer space, and from far beyond the earth the President of the United States broadcast Christmas greetings to the inhabitants of the world and beyond—in effect, opening the door to time's long unpredictable corridor of the Corps' second century of research, a century during which, be it peace, the marvels of science can lift man the world over to now undreamed heights of good living.

[1] The Nation's second active communications satellite, "Project Courier" was successfully launched on October 4, 1960. The communication-electronics portion of the system was developed under the technical direction of the U. S. Army Signal Corps.

Army Signal Corps Organization for Reseach and Development*

I. R. OBENCHAIN, JR.†, SENIOR MEMBER, IRE

Summary—**The Army Signal Corps organization for research and development is described. Research and development and combat development are closely related in the Signal Corps. The Office of the Chief Signal Officer staff in Washington and five Signal Corps field agencies have responsibilities in these areas. The relations among these five agencies as well as coordination with other key Signal Corps activities are summarized.**

This description of the Signal Corps organization for research and development seems appropriate for assisting readers to understand more readily the relations among the various Signal Corps activities engaged in this work.

Let us take a look at the chart (Fig. 1). The Chief Signal Officer, under direction of the Department of the Army staff, has as a portion of his mission the development, procurement, and distribution of communication-electronic equipment for the Army. The research and development part of this mission is integrated into the broad Army R&D program under the control of the Army Chief of R&D (now Lieutenant General Trudeau). The Chief Signal Officer also executes certain R&D projects on a reimbursable basis for other government agencies including Defense Atomic Support Agency, National Aeronautics and Space Administration, Advanced Research Projects Agency, the Navy, Marine Corps and the Air Force.

Within the Signal Corps, the R&D objectives are tied very closely to the Combat Development program. This program, within the Department of the Army staff, is the primary responsibility of the Deputy Chief of Staff for Operations and has as its principal objective the timely development of new organizations and materiel, and concepts for their employment.

The Chief Signal Officer carries out his R&D and combat development missions with the assistance of the five field agencies shown in Fig. 1. The Army Combat Surveillance Agency reports directly to the Chief Signal Officer. The remaining agencies, although commanded by the Chief Signal Officer, are under the staff supervision of the chief of the R&D Division of his office.

Let us first discuss the R&D Division, Office of the Chief Signal Officer and the activities under its staff supervision. The chief of this division is the Chief Signal Officer's "vice-president" for R&D and Combat Development. He and his immediate staff, in the name of the Chief Signal Officer, direct and control all of these programs unless specifically excepted (more about exceptions later). This responsibility includes all activities and functions concerned with basic and applied research, equipment and systems development and testing, the development of tactical and strategic applications and requirements; and the development of materiel, personnel, and organizational requirements for the introduction of new components, equipments and systems. Brigadier General Monahan, as chief of the R&D Division, is also Signal Corps Systems Manager for Air Defense Support, Missile Support, and Electronic Warfare Systems. The division of work among the four field agencies under his staff supervision is as follows:

The Signal Research and Development Laboratory conducts R&D in all areas of interest to the Signal Corps, unless specifically excepted. The Laboratory also provides, from its military support battalion, personnel to introduce new equipment into the Army.

The Signal Air Defense Engineering Agency provides research and development in support of the Army's air defense mission.

The Signal Missile Support Agency at White Sands Proving Ground conducts R&D in missile electronic warfare and in specified fields of meteorology and in communication-electronics supporting the missile program. This agency also provides frequency coordination and range communications and instrumentation operational services to the Commanding General, White Sands Proving Ground.

The Army Electronic Proving Ground conducts operational evaluation tests of major items and systems of communication-electronic-pictorial equipment for the Field Army before these items are submitted to the U. S. Continental Army Command for service or troop tests. These tests are conducted at Fort Huachuca, Ariz., after the developing agency has made necessary feasibility and engineering tests of the item. Operational testing includes electronic environmental and vulnerability testing. The Army Electronic Proving Ground also recommends and tests proposed organization and concepts for employment of new signal units.

Earlier mention was made of exceptions in the mission responsibility of the chief of the R&D Division, Office of the Chief Signal Officer. The major exceptions are in the areas of Strategic Communications and of Combat Surveillance. In each of these areas, the Chief Signal Officer has additional assistance. Another staff officer, the chief of the Army Communications Systems Division, has responsibility for strategic communica-

* Received by the PGMIL, July 11, 1960.
† Colonel, U. S. Army, USASRDL, Fort Monmouth, N. J.

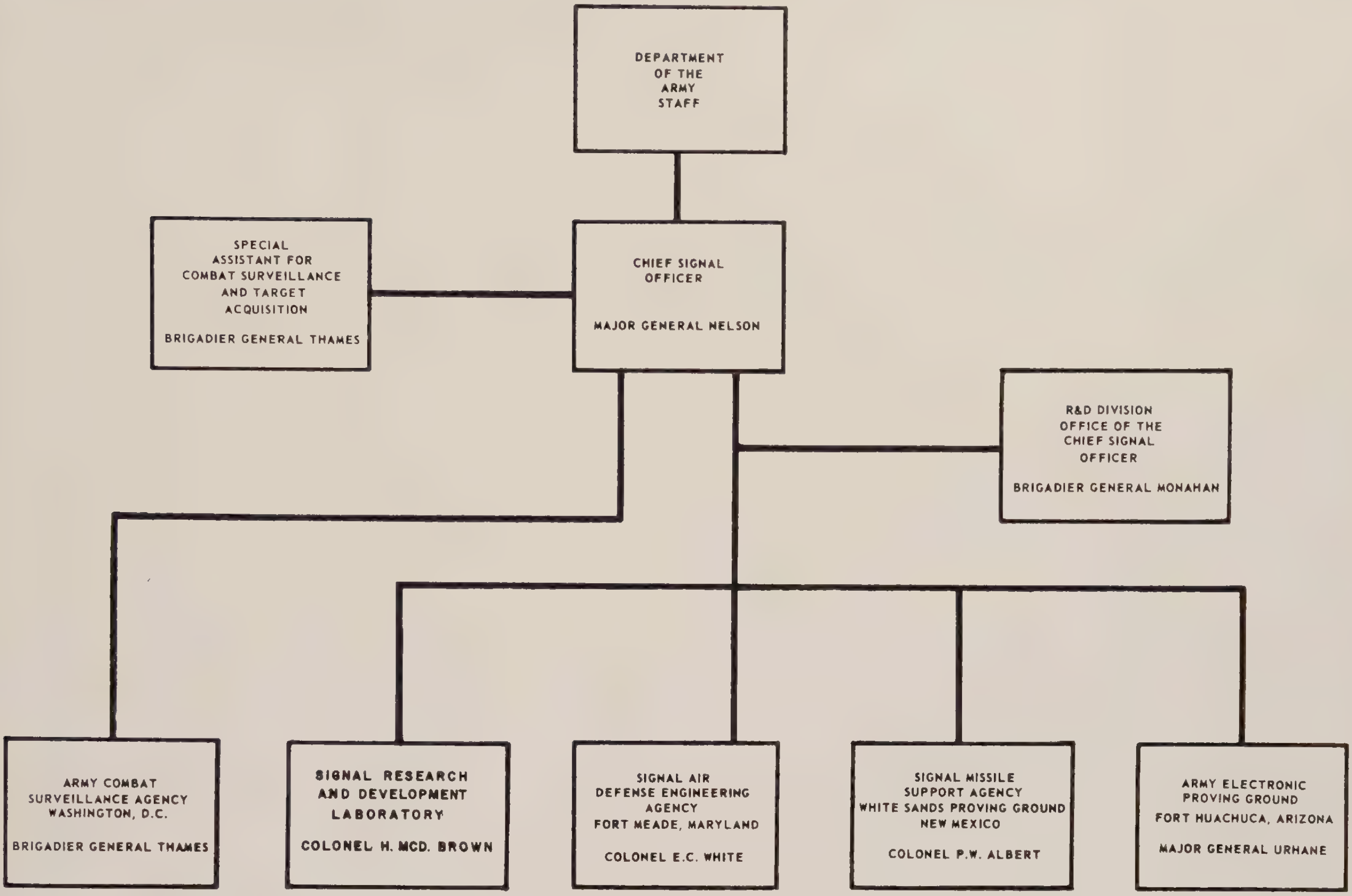

Fig. 1—Army Signal Corps Organization for Research and Development.

tion requirements and testing. The Commanding General, Army Combat Surveillance Agency, who is also Special Assistant to the Chief Signal Officer for Combat Surveillance and Target Acquisition, has special authority due to the Army's urgent need to improve its capability in this area. Brigadier General Thames, the present Surveillance Agency Commander, has personal responsibility and authority for the execution of the Chief Signal Officer's combat surveillance and target acquisition program. He normally works through the established staff of the Chief Signal Officer, but he may work directly with field agencies. This program has the highest priority within the Chief Signal Officer's command.

Although much Signal Corps R&D is done with internal resources, the major portion of the program is carried out by contract with universities, other nonprofit organizations, or with industry. Mention should therefore be made of the organization for preparing and executing these contracts. Signal Corps contracting, for both procurement and R&D, is under the policy control of the Signal Corps Supply Agency, Philadelphia, Pa. (Brigadier General Littell). This agency reports to the Chief Signal Officer's "vice president" for procurement and distribution in Washington, D. C. Because of the volume of business at the Army Electronic Proving Ground and at the Signal R&D Laboratory, separate procurement activities are operated at Fort Huachuca, Ariz., and at Fort Monmouth, N. J., respectively. These procurement offices furnish the contracting officers and handle the administrative side of the contracts, while the appropriate R&D activity furnishes the funds and the technical evaluation and guidance.

Located also at Fort Monmouth are the Signal Material Support Agency and the Signal Training Command. Close coordination between these activities and the R&D community is of course required since:

1) *The Signal Material Support Agency* is responsible for production engineering and the first production run of new equipment and for providing necessary literature to accompany new equipment to the field.

2) *The Signal Training Command* trains personnel to maintain and operate new equipment.

What has been described above is the "big picture" of the Signal Corps organization for R&D. No attempt has been made to list all of the specifics. The primary objective of this organization is to provide for the Army, in a timely fashion and consistent with the availability of resources, the best signal equipment and systems that can be developed.

The Signal Corps at the Space Frontier*

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Summary—The Signal Corps' research and development and operational mission responsibilities have created capabilities which readily lend themselves to applications in the space electronics field. The past accomplishments in satellite electronics and in satellite ground support are highlighted and an outline of future work is given.

THE flag-waving signalman, one hundred years ago, could hardly have responded with more than a touch of sympathy for the mental derangement of the prophet who would have suggested to him that within a century the Army Signal Corps was going to introduce military communications systems utilizing artificial earth satellites. To be fair, the signalman's reaction would not have been unique. The evolution in many fields of science and technology during the past 100 years has been so explosive, that our forefathers, confronted at that time with a preview of the things which came into being, would have had some good reasons to doubt their rationality. It should be expected that history will repeat itself in this respect during the next century, even on a bigger scale, and we may do well to be open-minded beyond the boundaries of concepts which appear comprehensible to us at the present.

For an activity which was not assigned a prime responsibility in preparing for the physical penetration of outer space, and which therefore was not involved in the fundamental technologies of rocket and missile developments, the Army Signal Corps has adapted itself to the support of space technology as well as to the vigorous utilization of the new techniques for its own missions in a remarkably short time. At least this is probably the impression an outside observer must obtain if he considers, for instance, that at this writing the payloads of 4 major satellites out of a total of 10 successful U. S. satellites, carrying orbiting scientific or application feasibility test equipments, have been created by the Army Signal Corps or under its technical supervision. Seen from the inside, this quick reaction is not surprising at all. It is very much the natural outgrowth of previous work in the electronics and communications field—the space age appears merely as a new and extremely fussy customer, for which many special considerations but, in general, no revolutionary processes of adaptation are required. The preparedness of the Army Signal Corps for Space Age Electronics was the result of research and development activities which have been carried out in the past in pursuit of normal mission assignments.

Throughout its existence, the Signal Corps' first order R&D responsibility has been in the communications field, with two basic objectives: to provide the Army with means to direct its troops in combat, and at the same time to receive back from the battlefront information on results and conditions. In a way, combat troops are being remote-controlled in their actions by communications, and they are being remotely interrogated by communications to report back their observations. Considering today's world-wide deployment of the Army, and radio as the most utilized medium of communications, the similarity of requirements for the basic military communications function and of those for operating satellites and space probes is quite obvious. The utility of all space devices depends on the ability to communicate with them for the purpose of initiating certain actions remotely, and of receiving back desired observation data. Satellite and space probe operations are indeed fundamentally communications problems, and the pursuit of their solutions was therefore a logical extension of normal Signal Corps philosophy.

The stringent requirement to make Army communications equipment suitable for quick mobility, rugged handling, extreme environmental conditions, and highest reliability in spite of all, has necessitated for many years a large R&D program of miniaturization and ruggedization of electronic parts, components, assemblies and systems, and associated efforts for environmental insensitivity, and reliability. The results of this endeavor have been so satisfactory that the Signal Corps was early in a position to offer to rocket and missile developers miniaturized electronics which could successfully survive the even more severe conditions of missile launching and flight. Thus, the Signal Corps has been engaged for many years in all phases of missile electronics and has been particularly close in relations with the Army Ordnance Corps. Furthermore, special components have been used in the missile electronics of other military services. The step from missile electronics to space electronics is relatively small. The main difference is the longer operational life requirement with the associated need to replace short time reliability by long life reliability. Although the long life reliability aspect will require serious additional efforts for those space projects which will have to operate for periods of many years, the Signal Corps was in a position to offer suitable space electronics for immediate use when the U. S. started its first satellite projects in 1955.

Parallel to this capability, resulting from components and materials R&D, another effort generated knowledge which related even more closely to satellite instrumentation and electronics, that is, the upper atmosphere rocket research program, which has been conducted within the framework of the Signal Corps' mission in

* Received by the PGMIL, July 11, 1960.
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meterology. This program has been active since 1945, using first German V2's and then smaller U. S.-made rockets to carry aloft instrumentation and telemetry equipment to study the higher regions of the earth's atmospheric envelope.[1] Experience from the work as well as from meteorological balloon instrumentation was almost directly applicable to space instrumentation.

In addition to the previously listed capabilities which mostly concern electronics to be carried by satellites and space probes, the Signal Corps—partly through R&D and partly through operational responsibilities—has been engaged in technological concepts which were readily applicable to the ground support required for space project operations, such as detection, tracking, and associated world-wide communications and data transmission services. The background in direction finding, radar, radar beaconry, missile range instrumentation, ionospheric and wave propagation research, and the existence of a world-wide communications network were the solid prerequisites for this additional capability.

These are, in brief, the major potentialities the Signal Corps was able to offer to space technology at the very start—and there were others which evolved from its mission in surveillance, electronic warfare and data processing.

The Signal Corps' interest, however, was not limited to supporting the Nation in every possible way on this new technological frontier. It held the conviction from the very beginning that direct utilization of space devices for better fulfillment of mission responsibilities was another important goal. Besides the employment of space devices for research purposes concerning wave propagation, ionospheric and atmospheric physics, the operational utilization of satellites for world-wide communications was, and is, the number one target since it now appears to offer the only suitable solution to a serious communications dilemma. Other operational utilization interests are related to the Signal Corps' responsibilities in reconnaissance, electronic warfare and meteorology.

As a result of this twofold interest—support to the over-all effort, and utilization for its own mission accomplishments—a number of significant contributions, including several important "firsts," to space electronics have been produced within the first five years of the space age. All of these items have already received broad coverage by scientific and popular news media and only a brief summary will therefore be given here with references to more detailed publications:

1) Preceding the advent of physical conquest of space by satellites and space probes, the Signal Corps stakes claim of having opened up the space age electronically in 1946 by bouncing radio signals off the moon from its Diana Radar of Fort Monmouth, N. J.[2] This famous experiment has since become routine and developed into an important tool for propagation research and has also resulted in practical communications concepts, as for instance, used by the U. S. Navy.

2) The Signal Corps' first contributions to satellite technology were made within the framework of the IGY under the sponsorship of the National Academy of Sciences and associated Department of Defense support.

a) The first officially assigned task was the technical operation and maintenance of the prime satellite tracking stations of the IGY Minitrack Network, and the provision of communications and data transmission between these stations, most of them in South America, the control center being located in the continental United States. This assignment was successfully carried out through the Signal Corps' Army Communications Systems Division.

b) As an associated task to the Minitrack Station operation, the need arose for calibrating the tracking equipment against objects radiating from space prior to the launching of satellites. The problem was resolved between Signal Corps and NRL scientists by illumination of the moon with the planned satellite radio frequency from the Fort Monmouth Diana Station and calibrating the Minitrack equipment against the reflected signals from the moon.[3] This exercise was highly successful. The illumination principle to "activate" nonradiating satellites was later expanded to a detection concept for "dark" satellites, which was first demonstrated on Sputnik I with the Fort Monmouth Station illuminating and the NRL Minitrack Station at Blossom Point, Md., as detector.

c) The first major satellite payload contribution was the solar power supply for the 6.4-inch IGY Vanguard test satellite 1958 Beta, launched on March 17, 1958, the first solar power supply ever flown on any satellite.[4] This solar supply, developed and produced at USASRDL, simple as it is, has broken down the prejudice which existed at the time towards the use of unconventional power sources in space application, and in now more than two years of satisfactory operation, has proven its space reliability. Much bigger and more complex solar power supplies including storage batteries have since been developed by the Laboratory or under its direction. The solar power supplies for satellite Explorer VII with a rating of 5

[1] H. J. aufm Kampe and J. R. Walsh, "USASRDL upper air research with rockets," IRE Trans. on Military Electronics, vol. MIL-4, pp. 216–222; April-July, 1960.

[2] J. H. Dewitt, Jr. and E. K. Stodola, "Detection of radio signals reflected from the moon," Proc. IRE, vol. 37, pp. 229–242; March, 1949.

[3] L. H. Manamon and A. S. Gross, "The Signal Corps Astro-Observation Center, Fort Monmouth, N. J.," IRE Trans. on Military Electronics, vol. MIL-4, pp. 327–331; April-July, 1960.

[4] W. Shorr, D. Linden, and A. F. Daniel, "Power sources designed for space," IRE Trans. on Military Electronics, vol. MIL-4, pp. 313–316; April-July, 1960.

watts, and for the TIROS satellite with an average rating of 19 watts are significant examples.

d) The second major satellite payload contribution was the complete electronics payload for the IGY Vanguard Cloud Cover Satellite, 1959 Alpha, launched on February 17, 1959.[5] The complex electronics of this first successfully launched full-size Vanguard satellite, which had infrared scanning devices to provide crude mapping of the earth's cloud cover and a tape recorder to store the information, operated perfectly during the entire 20 days of the life of the battery power source during which it made 211 orbits and was successfully interrogated 155 times to release the stored information. Unfortunately, subsequent picture computation became impractical, due to a mechanical mishap in the launching procedure which sent the satellite tumbling through space rather than in the required spin stabilized mode. From the space electronics viewpoint, however, valuable experience was obtained.

e) Throughout the IGY satellite program, the Signal Corps has also contributed special components or subsystems, such as high-frequency control crystals, special batteries, and high efficiency, low voltage to high voltage transistor power converters to the payloads developed by other organizations.[6]

3) The first prototype of a communications satellite and, in fact, the first test of any satellite for direct practical applications was successfully launched on December 18, 1958. Project SCORE (Signal Communications via Orbiting Relay Equipment) was an ARPA sponsored project carried out by the Signal Corps with the Air Force providing the Atlas launching vehicle.[7] The significance of this experiment, well-publicized through its association with the President's Christmas message from outer space, lies in the fact that it effectively demonstrated the practical feasibility of world-wide communications in delayed and real time mode by means of relatively simple active satellite relays. During the 13 days' battery life, the satellite was interrogated by Signal Corps ground stations 78 times, using voice and teletype messages for the communication tests with excellent results, and provided valuable information for the design of future communications satellites.

4) The first television-type satellite for world-wide cloud cover mapping [Project TIROS (Television and Infrared Observation Satellite)] produced under Signal Corps technical supervision and NASA sponsorship was successfully launched on April 1, 1960, by an Air Force Thor-Able vehicle.[8] The electronics of this satellite, including two TV cameras of different resolution for direct readout and tape storage, and an intricate control and programming center, represents the most complex concept so far used in a satellite. Many thousands of excellent pictures of the cloud cover of major portions of the world have been obtained by this device and have given meteorologists valuable new information on the weather machinery. In addition to having been responsible for the technical supervision of the development of satellite and ground equipment, the Signal Corps operated the primary command and readout station located in the continental U. S., at Fort Monmouth, N. J. Technical supervision was also provided for the second ground command station located at Kaena Point, Hawaii, which was operated under contract. The TIROS project was the second Signal Corps developed or technically supervised satellite electronics, the results of which were considered to be of such national importance that the President personally released the first information to the world again.

5) In addition to the well-recognized payload and ground support contributions, the Signal Corps has also been very active in the special aspects of R&D which have been opened up by the space age and in those which are required to assure further progress in the space effort. One of these aspects concerns the observation and study of the radio emissions from space devices. Since the first hours of Sputnik I, the Laboratory at Fort Monmouth has continuously, on a 24-hour, around-the-clock basis, observed and recorded the important signal characteristics of every USA and USSR satellite and space probe, and established probably the world's most complete space signal library.[3] In addition to very valuable information on wave propagation and ionospheric parameters which will aid in designing future space communications systems,[9] much data have been obtained which proved important for the quick performance appraisal of launching vehicles, for orbit determination, and for satellite and space probe tracking. A close working relationship has been developed during the last two years between the USASRDL Astro Observation Center, consisting of the Deal and Diana

[5] R. Hanel, J. Licht, W. Nordberg, R. Stampfl, and W. Stroud, "The satellite Vanguard II: cloud cover experiment," IRE Trans. on Military Electronics, vol. MIL-4, pp. 245–247; April-July, 1960.

[6] J. P. McNaul, "Electronic components for space instrumentation," IRE Trans. on Military Electronics, vol. MIL-4, pp. 308–312; April-July, 1960.

[7] S. P. Brown, "Project SCORE: signal communication by orbiting relay equipment," IRE Trans. on Military Electronics, vol. MIL-4, pp. 193–194; April-July, 1960.

[8] H. I. Butler and S. Sternberg, "TIROS—the system and its evolution," IRE Trans. on Military Electronics, vol. MIL-4, pp. 248–256; April-July, 1960.

[9] P. R. Arendt, "Review of USASRDL satellite propagation studies," IRE Trans. on Military Electronics, vol. MIL-4, pp. 357–358; April-July, 1960.

F. O. Vonbun, "Analysis of satellite motion from radio reception," IRE Trans. on Military Electronics, vol. MIL-4, pp. 359–363; April-July, 1960.

facilities, and all national agencies concerned with tracking of space objects. As a result of this activity, the Signal Corps has also been assigned a part in the project concerned with the establishment of the global U. S. space tracking net under ARPA/NASA sponsorship. The Army Communications System Division is conducting this work, with USASRDL at Fort Monmouth carrying the R&D phases. Other R&D efforts to prepare for future needs of space electronics relate particularly to long life, reliable microwave components, antenna concepts, power sources and all other electronics aspects which will be essential for future communications satellites as well as other space applications.

The Signal Corps is already deeply involved in the development of the next generation of experimental communications satellites. The delayed repeater type, so successfully demonstrated in SCORE, has already evolved to a highly sophisticated advanced design with the tremendous communications capacity of more than $\frac{1}{4}$ million words per interrogation. This satellite Project "COURIER" is nearing completion and is likely to be launched during 1960.[10] The real time repeater concept with the goal of the 3 synchronized satellites in a 24-hour orbit is being pursued under Project "ADVENT" with experimental systems expected to be launched within a few years. Both the "COURIER" and the "ADVENT" projects sponsored by ARPA, are, of course, of vital interest to the Signal Corps for its own needs, as well as for its assistance to the Nation's operational needs in military communications.[11] This interest, however, is not limited to the active satellites carrying life electronics. The Signal Corps is also participating in the exploration of passive orbiting devices of every size, from large balloons down to molecular particles, for new and better ways of communications.

This, in brief, is the status of the Signal Corps' role at the space frontier as it appears at the time of its first centennial. It goes without saying that many of the past and future accomplishments have been and will be the result of a close-knit team effort with industry, universities, colleges and of cooperation with other military and civilian government agencies. All of these, which cannot be listed here, deserve high credit and share the Signal Corps' pride in its early success at the Space Frontier. It is hoped that the Signal Corps' experience and capabilities in the field of space electronics can be utilized in increased measure for the benefit of the Nation's effort in exploring and utilizing space for the safety and the welfare of our country.

[10] The Army Signal Corps Courier satellite was successfully launched on October 4, 1960. G. F. Senn and P. W. Siglin, "Courier Satellite Communication System," this issue, p. 407.

[11] C. D. May, Jr., "The significance of satellites for military communications," IRE Trans. on Military Electronics, vol. MIL-4, pp. 176–183; April-July, 1960.
T. Mottley, D. Marx, W. Teetsel, "A delayed repeater satellite communication system of advanced design," IRE Trans. on Military Electronics, vol. MIL-4, pp. 195–207; April-July, 1960.
J. E. Bartow, D. L. Jacoby, G. N. Krassner, "Progressive communication satellite systems design," IRE Trans. on Military Electronics, vol. MIL-4, pp. 208–215; April-July, 1960.

Courier Satellite Communication System*

G. F. SENN†, SENIOR MEMBER, IRE AND P. W. SIGLIN†

Summary—**This paper on the Courier satellite presents some of the background against which this experiment on an operational satellite communication system is being conducted. Details on the development, construction and testing of both the ground and orbiting segments of the system are outlined. Information on the results expected from the operational aspects of the experiment are also presented.**

THE Courier communications satellite successfully launched on October 4, 1960 is now demonstrating the possibilities of operating a communications system capable of handling an economically significant amount of traffic over global distances. Project SCORE[1] experimental satellite demonstrated that a communications satellite system was feasible. However, it was limited by the vehicle, by time, and by available components to providing a single voice channel or seven teletype channels. This, along with the restricted locations of the ground stations and the relatively low orbit, permitted a traffic rate of only 2800 words per station, per pass. The Courier satellite, taking advantage of advances in missile technology, of newly developed solid state devices and more sophisticated communication techniques, is designed to handle up to 360,000 words

* Received by the PGMIL, September 19, 1960.
† USASRDL, Fort Monmouth, N. J.

[1] S. P. Brown and G. F. Senn, "Signal communication by orbiting relay experiment," Proc. IRE, vol. 48, pp. 624–630; April, 1960.

per pass, per station, for a total of four stations.

The Courier satellite has been specifically planned to test not only the equipment design concepts, but to investigate thoroughly the traffic handling capabilities of a satellite communication system (Fig. 1). Sufficient missile launching capability is now available to place 500 pounds of payload in a 750-statute-mile orbit. Solar cells have been developed to provide charging current for a power supply with long life, and technology has advanced to a point where, within this payload, a communication radio relay repeater of sufficient capacity, to be competitive with conventional types, has been realized.

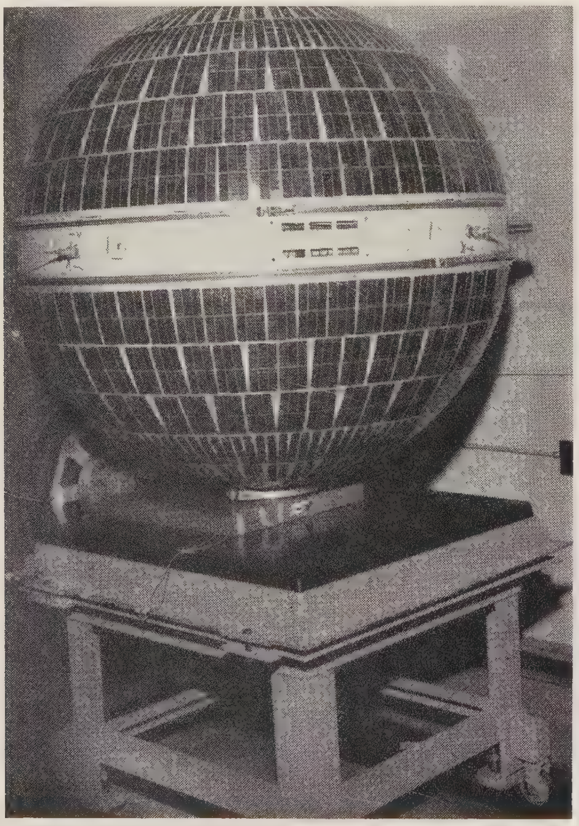

Fig. 1—Satellite exterior.

The Courier satellite has been designed for an anticipated life of one year. Redundancy is provided in all active elements where the additional parts do not add complexity. Those components which could not profitably be made redundant are standard solid-state circuitry of proven reliability. Limiting the use of thermionic electron tubes to the power output stage of the communication transmitters reduced the power consumption to a minimum and insured another increment of reliability. Mechanical linkages have been eliminated to the irreducible minimum, existing only in the tape transport mechanisms, frequency control assemblies, code tape readers and a few necessary relays. Even if, through some unavoidable accident or failure, less than the entire design life is achieved, more than enough experience can be obtained to investigate thoroughly and prove the operational capabilities and economic feasibility of both delayed- and real-time satellite radio relay systems.

A description of the operation of this active relay communications system follows. As the Courier satellite approaches a ground station, a direction finder located near that ground station will determine the azimuth of the satellite's approach and transmit same to the antenna operator at the Courier site. The direction finding set will respond to an acquisition beacon which is transmitting on nominal 108 Mc at all times that the satellite is in a standby condition.

On receipt of information from the direction-finding site, the Courier ground station antenna operator will position the antenna in the general direction indicated by the direction finding equipment and place the Courier antenna in sector scan mode of operation. When the signal from the satellite acquisition beacon is received by the Courier antenna, an indication thereof will appear at the antenna operator's console and at the Courier station operator's console. The station operator will then issue over the VHF (150-Mc) ground-to-satellite system the command which will turn on the microwave communication receivers and transmitters in the satellite, disable the acquisition beacon and activate a higher-power telemetry transmitter on the same frequency as the acquisition beacon. When microwave transmitters become operable, the ground antenna can be placed in automatic tracking mode of operation on the communication link frequency (1700 to 1800 Mc).

The VHF for the acquisition, telemetry and command link was chosen to facilitate these functions through the relatively wide beam widths characteristic of antennas at these frequencies and to comply with existing telemetry standards. The UHF communication link was selected to provide bandwidth required for the data traffic capacity and to simplify the design of the automatic tracking ground antenna, in addition to the noise and propagation advantages at these frequencies. Once the communication link has been established, commands can be issued over either or both links.

A normal operation will be for the ground station to command the satellite to transmit down the data stored in the tape recorder assigned to that particular ground station. At the end of a four-minute transmission from the satellite to the ground, the contents of that tape recorder will have been received and recorded at the ground station. Simultaneously, with the receipt of these data, the ground station can command another satellite tape recorder, assigned to succeeding ground stations along the orbit, to record traffic addressed to that particular ground station. This can be repeated for each of the tape recorders, of which there are four allocated for the transmission of teletype data in digital form. This process can be continued for all of the time that the satellite is in view of the ground station, recording on each of the tape recorders a maximum of four minutes of teletype data at the rate of 55 kilobits per second. This represents a storage capacity of 13,200,000 bits, equivalent to 300,000 words. On the completion of the

traffic interchange between the ground station and the satellite and prior to the satellite's passing out of view of the station, the ground station will command the satellite electronics to revert to the standby condition with the acquisition beacon only transmitting. Should the ground station fail to issue this beacon-only command, the satellite will, after a 20-second delay, automatically revert to the standby condition.

Alternatively, if so desired, the ground station can place on the fifth recorder in the satellite four channels of voice communication for a total of four minutes. This particular recording circuit is an analog type, and in addition to voice, will accept any analog-type communication that can be accommodated in a 300- to 50,000-cycle bandwidth.

As the satellite approaches succeeding ground stations along its orbit, this sequence can be repeated successively to transmit and receive traffic along the path of the satellite. The separation between stations is immaterial to the operation of the satellite in this delayed repeater mode. By the appropriate location of ground stations at centers where ground communication can be assembled and concentrated, the Courier satellite can perform as a transmission medium for all traffic which would not be affected by the delayed nature of the transmission.

In addition to this Courier method of communication, the satellite can be used as a real-time radio relay repeater. This is accomplished by the ground station which first acquires the satellite signal commanding the satellite to operate in a real-time mode of operation in which the satellite microwave receivers and transmitters are connected so that signals received from the ground are transmitted immediately. The satellite, of course, at the time this command is given, must be in view of two or more ground stations simultaneously. The second ground station can then receive the transmission from the first ground station directly through the satellite. Each of the two or more ground stations can transmit either teletype or analog communication on a push-to-talk basis as long as the satellite remains in direct line-of-sight of each of the stations involved. On completion of the communication, the second ground station can then either command the satellite to standby or, if line-of-sight time is still available, can place traffic in the appropriate satellite tape recorder for delayed transmission to succeeding ground stations.

Based on an expected 750-statute-mile approximately circular orbit, the ground station-to-satellite VHF and UHF links were designed to the parameters listed in Table I.

The Courier satellite is a sphere 52 inches in diameter, weighing 500 pounds. Approximately 80 per cent of the surface area of the fiberglass and epoxy sphere is covered with 19,152 solar cells which are shingled together and mounted on the satellite in modules. The internal structure of the satellite comprises central, upper and lower honeycomb fiberglass and epoxy platforms supported on aluminum tubing truss members.

TABLE I

SATELLITE FREQUENCIES

Communication	
Receiving	Nominal 1.7 to 1.8 kMc
Transmitting	Nominal 1.8 to 1.9 kMc
Acquisition and Command	
Receiving	Nominal 150 Mc
Transmitting	Nominal 108 Mc
Storage Capability	13,200,000 bits in each of four magnetic tape recorders
Transmission rate	55,000 bits/second

UHF Circuits

	Satellite	Ground Station
Power output	4 watts	1000 watts
Noise figure	14 db	—
Noise temperature	—	640°K
IF bandwidth	550 kc	100,200 or 500 kc
Antenna gain	−4 db	41 db
Antenna polarization	Linear	Circular transmission, diversity reception
Carrier-to-noise ratio at 3000 miles Slant Range		
Satellite-to-ground	22 db	
Ground-to-satellite	21 db	

VHF Circuits

	Satellite	Ground Station
Standby power output	50 mw	—
Active power output	1.5 watts	100 watts
Noise figure	8 db	4 db
IF bandwidth	30 kc	6 kc
Antenna gain	−4 db	19 db
Antenna polarization	Circular	Linear transmission, diversity reception
Carrier-to-noise ratio at 3000 miles Slant Range		
Satellite-to-ground standby	18 db	
Satellite-to-ground active	25 db	
Ground-to-satellite	32 db	

The electronic components of the satellite are mounted on both the upper and lower surfaces of each platform and interconnected with a massive wiring harness which circles the outer edge of the central platform (Fig. 2). To attain access to the components and for ease of handling, the solar sphere is split into two hemispheres which are connected by a magnesium band forming the circumference of the center platform. Four VHF whip antenna assemblies are equally spaced around the central magnesium band. Two notched-fin UHF antennas are located at antipodean points on the magnesium band. The shell material consists of honeycomb fiberglass sandwiched between two thin fiberglass layers with a conducting metallic surface covered by a third fiberglass layer.

Fig. 3 is a simplified block diagram of the satellite electronics. This complex electronic package utilizes approximately 1300 transistors and diodes and two operating vacuum tubes in performing the mission of relaying messages from station to station on the earth's surface.

The VHF satellite circuitry provides for a tracking beacon, telemetry, command acknowledgment and satellite acquisition. The four VHF antenna whips located in the satellite equatorial plane are electrically fed in quadrature. This arrangement results in a circularly-

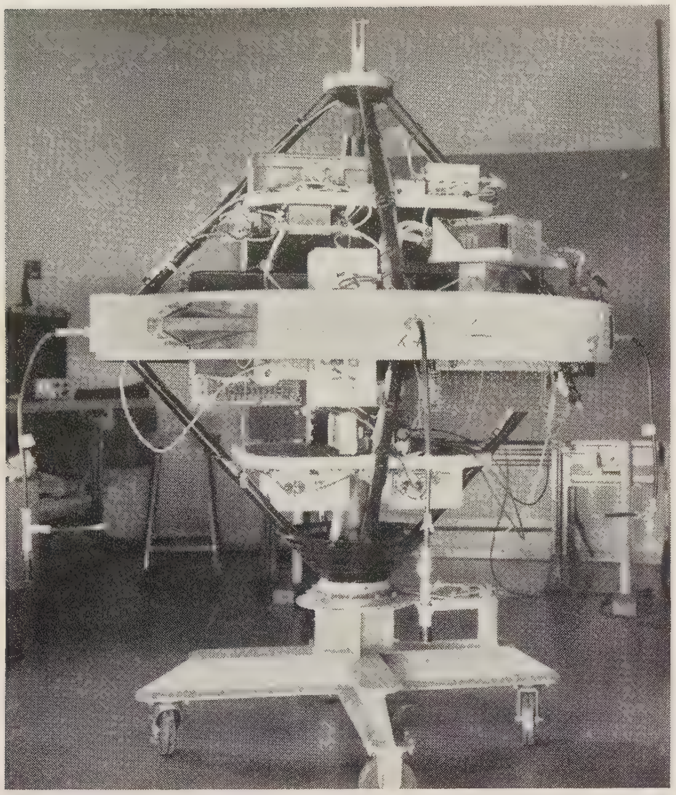

Fig. 2—Satellite interior.

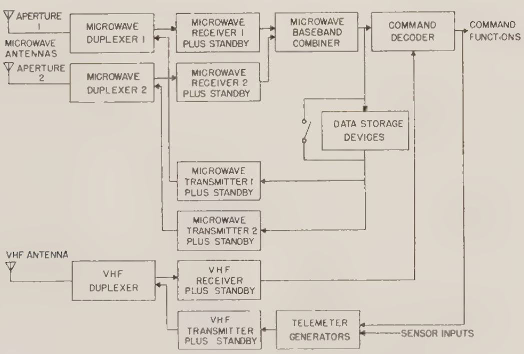

Fig. 3—Courier satellite block diagram.

polarized antenna pattern along an axis normal to the plan of the whips. Two VHF receivers alternately switched on and off by a power-saver switching circuit continually search for an RF signal from a ground station. Once a signal has been received, the power-saver circuit is locked out and the receiver which received the initial signal remains energized for the remainder of the orbital pass. Each receiver is a completely transistorized single conversion superheterodyne unit with a noise figure of 8 db. A crystal-controlled local oscillator is employed. Through the use of a crystal filter, a bandwidth of 30 kc at an IF frequency of 10.7 Mc is achieved. Both receivers have emitter-follower output stages which are coupled to a common output terminal. These output stages are designed to present a high impedance when the transistor is inactive. In this way, redundancy in VHF receiver capability is achieved without switching the outputs.

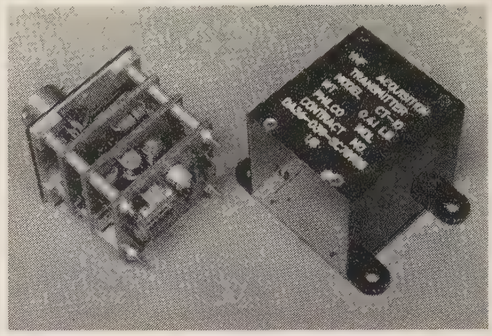

Fig. 4—VHF acquisition transmitter.

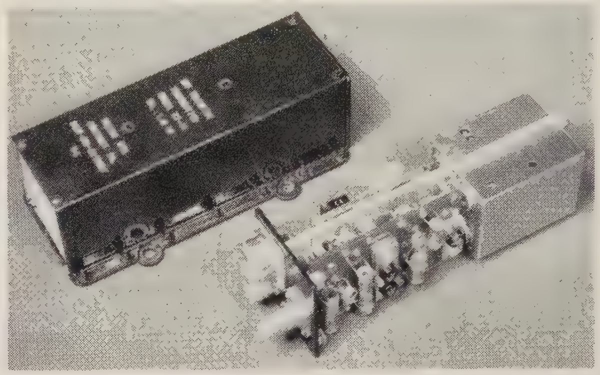

Fig. 5—VHF telemetry transmitter.

The VHF beacon and telemetry transmissions are provided by separate transmitters (Figs. 4 and 5). Redundant units are installed which can be switched into operation by the proper command from the ground station. All transmitters are completely transistorized, with the beacon radiating 50 mw of power during the inactive portions of the satellite orbit, and the telemetry transmitter 1 watt when the satellite is fully operational. The frequency of both transmitters is maintained to within ± 0.002 per cent by crystal controlled oscillators. The beacon transmitter output is an unmodulated CW signal, and the telemetry transmitter is frequency modulated by subcarrier oscillators to provide telemetry data on 35 satellite parameters.

The communications traffic link between satellite and ground stations operates in the UHF portion of the frequency spectrum. This selection was based on propagation advantages, freedom from noise and interference, and component availability. The UHF notch antennas provide continuous pattern coverage through a solid angle exceeding a hemisphere. Separate UHF receivers with permanently connected backup units detect the microwave signals at each antenna. Two transmitters operating at frequencies spaced approximately 20 Mc apart provide frequency diversity transmission from the satellite to the ground station. The output of all the receivers is combined at baseband. Permanently connecting the four receivers in this manner results in the loss of 3 db of RF signal when compared with circuit switching; however, the operating reliability is considerably increased. The unique design of the baseband combiner utilizes a 200-cycle pilot

tone transmitted from the ground station to actuate the removal of a defective receiver from the output circuit without switching, should the pilot tone be absent from the output of the offending receiver. Each of the four UHF receivers is a single-conversion superhetrodyne employing a three-pole passive preselector, second harmonic mixing, and 30-Mc IF amplifier (Fig. 6). These completely transistorized receivers provide a noise figure of 14 db and an IF bandwidth of 550 kc and consume 1.5 watts of power. As an aid to achieving this low noise figure for a transistorized unit, each chassis of the receivers is gold plated. Technicians wore cotton gloves in the assembly and testing of these components to avoid contamination of the gold surface.

The four microwave transmitters, two primary and two redundant units, provide 4 watts of power for the satellite to ground message link (Fig. 7). Both operating transmitters are frequency modulated by the same signals. A redundant transmitter pair can be switched into operation upon command from a ground station. Each transmitter is a self-excited cavity oscillator compensated by a mechanically coupled motor-driven automatic frequency control (AFC) system. A crystal-controlled multiplier chain provides the reference signal for AFC. With this arrangement, the transmitter can be locked into frequency within 40 seconds after turnon with a frequency stability of 0.005 per cent. The frequency is controlled by a tuning screw driven by a two-phase 400-cycle ac motor controlled by a discriminator circuit. Each transmitter is hermetically sealed in a welded magnesium case to insure reliable operation of the mechanical AFC circuit in the environment of outer space. A novel wax-filled heat sink of large energy storage capacity is employed in cooling the anode of the transmitter tube during operation. This ingenious heat sink depends upon the change of wax from a solid to a liquid state when heated for the heat storage capacity.

The recorded messages are stored on five miniature magnetic tape recorder-reproducer machines. The recorder is designed to provide opposite direction recording and playback. This causes traffic to be read out backwards and requires a compensating traffic reversal elsewhere in the system. Erasure of old traffic is automatically accomplished by a permanent magnet during the playback cycle. Each recorder weighs five pounds and consumes 10 watts of power. The recorders are hermetically sealed in welded aluminum cases to insure operation of the mechanical components within a space environment.

The satellite is powered by nickel-cadmium batteries which are charged by a solar cell generator. The charge condition of the batteries is an essential parameter which determines the possibility and duration of a message traffic exchange between the satellite and the ground station during an orbital pass. If the battery charge is too low, further solar charging is required before a message exchange can be accomplished. The information concerning the condition of the batteries is

Fig. 6—UHF receiver.

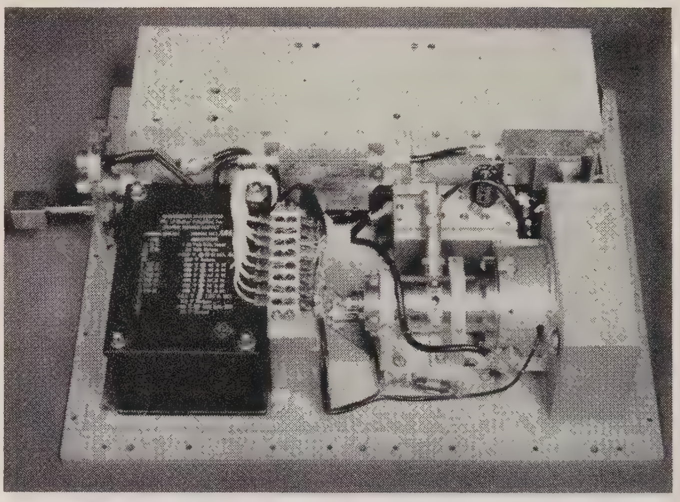

Fig. 7—UHF transmitter.

available to the ground station over the VHF telemetry link. The satellite "standby" power requirement between message exchange periods is 13 watts; the peak power demand during full duplex message exchange is 225 watts. The solar charging cycle is dependent on orbit considerations. The Courier satellite requires charging during approximately 60 per cent of the total orbital period to provide sufficient power from the solar cell generator for adequate operation. The solar cell generator array comprising 19,152 solar cells provides 60 watts of instantaneous power for charging batteries (Fig. 8).

Commands selected by a ground station operator are transmitted to the satellite over both the VHF and UHF transmission links. The various commands to control the operation of the satellite components, such as tape recorders and microwave transmitters, are coded to insure privacy of operation. A complete Courier ground station is housed in three semi-trailers and one maintenance van (Fig. 9). The semi-trailers provide for communications coordination control, operating console and message processing center, and a radio van containing all the UHF and VHF receiving and transmitting equipment. The antenna system requires a rein-

Fig. 8—Satellite solar cells.

Fig. 9—Ground station.

forced concrete pad to support the 40-foot tower and 28 foot parabolic reflector. The station normally operates from commercial 60-cycle 120/208 three-phase, four-wire, wye-connected ac power. To insure operation during a commercial power failure, four 45KVA engine generators with a power change-over switch are also provided. The entire ground station is a semi-fixed installation which may be dismantled, transported, and reassembled at another location requiring only the installation of a reinforced concrete pad to support the antenna.

A simplified block diagram for the entire ground station is shown in Fig. 10. In the VHF portion of the station, a system of polarization diversity reception is employed with switching provided to permit either horizontal or vertical linear transmission. The UHF system uses circular polarization on transmission, but for reception depends upon a unique quadruple diversity system providing both frequency and polarization diversity. The antenna feed comprises feed elements for both UHF and VHF, as well as a motor-driven lens

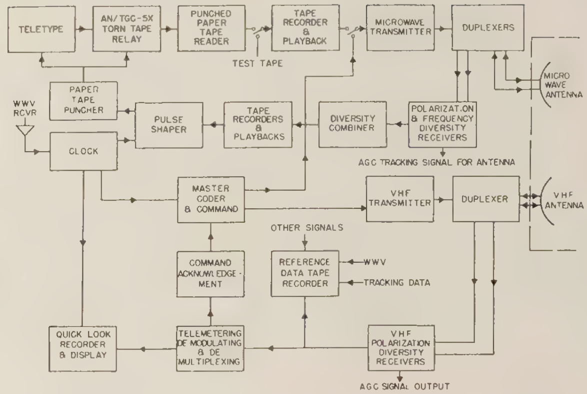

Fig. 10—Courier ground station block diagram.

scanner to provide conical scan at UHF as part of the automatic tracking antenna system. Antenna tracking accuracies of 0.5° at slew rates of 15°/second have been demonstrated. The antenna beamwidths are 18° at VHF and 1.35° at UHF.

All beacon and telemetry signals from the satellite are received at the ground station over the VHF equipment. The initial command to activate the Courier satellite is transmitted over the VHF link to the satellite. Telemetry data are recorded in both strip-chart form and on magnetic tape. The strip-chart telemetry record provides a real time telemetry analysis capacity that is particularly useful in determining battery voltage conditions and tape recorder positions in the early moments of a ground station to satellite operating sequence.

The VHF receivers are of the double superheterodyne type with a dynamic range of −155 to −110 dbw for beacon signals and −145 to −90 dbw for telemetry signals. Phase lock techniques allow the use of narrow detection bandwidths of 1 kc for beacon and 6 kc for telemetry signals. Automatic signal search circuits are disabled when phase lock is accomplished. A noise amplitude detected signal from each receiver is added to a phase detected combined AGC signal to maintain equal gain in both receivers.

All message traffic to and from the satellite passes through the UHF equipment in the ground station (Fig. 11). The satellite uses a frequency diversity system of transmission to minimize the transmission effects of the satellite spinning and tumbling through outer space. For this reason the ground station receiving system comprises four parametric converters used in a double conversion superheterodyne system to provide both frequency and polarization diversity reception at the ground station. Both predetection and postdetection signal combining are used in the receivers because the satellite transmitters used in the frequency diversity satellite transmission are noncoherent. The receiving system has a dynamic range of −140 to −100 dbw. Received signals at separate frequencies and of either linear polarizations are fed to each of the four parametric converters. Both automatic phase and frequency

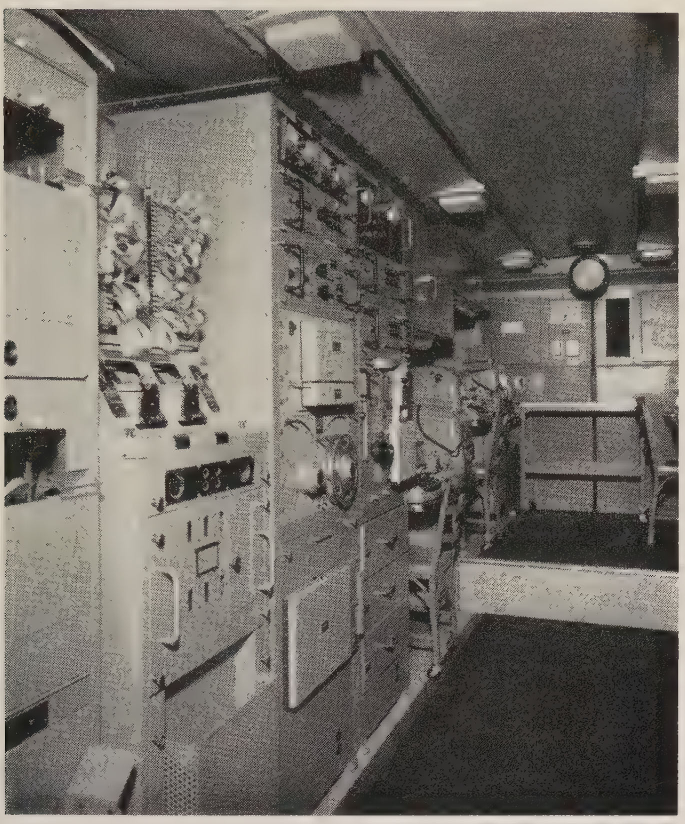

Fig. 11—Ground station van interior.

control maintain a constant phase relationship through the receivers. Combining the signals from the diversity receiving system is done at baseband by linear limiters and cathode-follower adders.

Teletype message traffic supplied to the ground station is processed through several speed buffering techniques in order to achieve the high storage capacity of the Courier System. Teletype messages on perforated paper tape are read by a paper tape reader to convert the paper tape perforations into electrical signals which are recorded on magnetic tape at a speed of 1.68 ips (200 characters/second). The magnetic tape is then played back at a speed of 60 ips (7140 characters/second) and the electrical signals are converted from parallel to serial form and used to frequency modulate the UHF signal transmitted to the satellite at a rate of 55,000 bits/second. Signals returning from the satellite are converted from serial to parallel form and recorded on magnetic tape at a tape speed of 60 ips. This tape is then played back at a speed of 1.68 ips and the electrical output signals are used to actuate a paper tape perforator to punch paper tape usable by a standard teletype machine. Using these speed buffering techniques, an amazing amount of message traffic can be transmitted to and stored by the satellite.

Recorded voice or analog traffic is handled in a different manner. The analog message is initially recorded on magnetic tape at unity speed. The tape is then reversed and played back to the satellite at twice unity speed. When analog traffic is received from the satellite, it is passed through a band-pass filter, with an LF cutoff adjusted to approximately 300 cycles to eliminate the 200-cycle pilot tone always present in the received signal, and is then recorded on magnetic tape at twice unity speed. When played back at unity speed, the original voice message will be recovered.

When the satellite is in a position along the orbital path where it can operate simultaneously with two ground stations, message traffic, either digital or analog, can be transmitted on a real-time basis between stations in much the same manner as described above. In real-time operation, however, the message data are not recorded in the satellite and the use of frequency multiplex equipment permits four voice messages to be transmitted simultaneously between the ground stations.

The Courier satellite has at the time of this writing completed 26 orbits. Of these, 11 have been usable for both of the ground stations including the first days of the experiment during which activity concentrated on insuring that all of the components of the system were operating properly and in handling special messages not related to the testing function. A tremendous volume of simulated traffic has been carried. Even though the system has not been operated to full capacity about six million words of teletype information have been transmitted daily between the ground station at USASRDL, Fort Monmouth, N. J. and the Puerto Rico station located at Salinas. This is a significant portion of the daily military administration transatlantic traffic, most of which would not be adversely affected by the short transmission delay of the Courier satellite system operating in delayed repeater mode. Since there are no limitations on the location of ground stations in the east-west direction and since up to four stations can be integrated into this system, it can easily handle a share of this traffic.

The communications system itself has far exceeded the expectations of its designers. The received power at the ground stations has averaged above −95 dbm which is approximately 10 db higher than was anticipated by the initial design. Much of this improvement was obtained by the excellent performance of the diversity combining system used in the ground station; the exact advantage of which could only be estimated at the time the design was undertaken. Error rates on teletype traffic have been consistently low and although exact figures are not available on standard transmission copy, those obtained using built-in error counting facilities indicate a rate of about 1 to 2 errors in 2000.

Even in the short period of its operation the Courier satellite system has demonstrated a capacity competitive with transatlantic high frequency radio and cable links. With the refinement of techniques it is reasonable to assume that the system can be made competitive from an economic viewpoint. Detailed analysis after a longer period of operation of this experimental system will confirm or disprove this assumption.

Exploratory Research in the Signal Corps*

N. J. FIELD† AND I. A. BALTON†, MEMBER, IRE

Summary—This paper reviews the USASRDL exploratory-research program from its inception in 1958 to its current state of development. The treatment centers about three main parts: background and philosophy of exploratory research in the Signal Corps, implementation of the program at USASRDL, and major achievements.

The introductory portion deals with a discussion of the motivation that led to a delineation of exploratory research as a modified basic-research concept, and the activation of an exploratory-research program. This discussion is followed by an exposition of the program and of the scientific areas that are currently being investigated. The article then gives a summary of the important accomplishments resulting from the program. A brief report is also given of plans for the initiation of new research tasks in the future.

LATE in 1957, coincident with the added impetus furnished by the successful launching of Sputnik I and the consequent ushering in of the Space Age, USASRDL embarked on a program of exploratory research. This program, which had been in the process of maturing for a number of years, embodies a novel philosophy of research—a philosophy that has broken loose from the fetters of traditional concepts that distinguish basic from applied research. Today, on the occasion of the Signal Corps Centennial celebration, it is appropriate to offer a brief review of exploratory research in the Signal Corps. In this review, we discuss the background that led to the new concept, the realization thereof, some significant results, and plans for the future.

The advent of international missile and satellite races has resulted in a marked increase in government support of scientific research. Dollar-wise, the 1961 federal budget includes research and development funds that are about 30 per cent higher than the 1959 outlay. This budget includes $600 million for basic research alone ($100 million above the 1960 figure). L. V. Berkner[1] reports a noticeable change in American attitudes toward science and education. Although he reports both negative and positive sides of the accomplishments ledger, Berkner lists the following gains: 1) appointment of a Science Adviser to the President and instatement of the President's Science Advisory Committee; 2) restoration of cuts in Department of Defense funds for science and technology; 3) increase in appropriation for the National Science Foundation; 4) passage of the 6-year student loan bill; 5) creation of the National Aeronautics and Space Administration (NASA); 6) creation of the Advanced Research Projects Agency (ARPA); 7) restoration of research facilities in the field of atomic energy; 8) appointment of a Science Adviser to the Secretary of State; 9) improvement of conditions of scientists employed in government positions; 10) creation of a House of Representatives Standing Committee on Science and Astronautics; and 11) revision of science curricula in the nation's schools.

Within USASRDL, this change of attitude has been reflected in the increased encouragement and support given to this new concept of exploratory research. The architects of the USASRDL research program recognized that the coming decade would be one that would make great technical demands and that would require a complement of personnel capable of wisely administering a research program. Such a capability would be sorely lacking in an organization that stressed a large contractual program to the exclusion of well-planned, well-directed internal research. The planners took into account the pitfalls of a large contractual effort—one of which is the certain deterioration of internal research and development capabilities. Prosecution of a contractual program of necessity causes diversion of talented scientific and engineering personnel to nontechnical duties. Such diversion, if continued, eventually leads to a plateau of technical competence, or more likely, a degradation thereof. An atmosphere of this nature is certainly unattractive to young technical personnel who are interested in professional growth. Thus, as reported by H. A. Zahl and E. M. Reilley,[2] perpetuation of this situation would inevitably lead to a decay in the technical capability of the organization, the end result of which would be the lack of scientific imagination necessary to wisely administer government research and development.

Further reasoning along these lines led to the inescapable conclusion that, to maintain adequate scientific competence within our laboratory, we must insure a steady influx of talented young scientists. These people are normally attracted by positions that give them opportunities to conduct independent research, to use their scientific imagination, and thus to develop their eventual ability to plan and make policies. Motivated by the desirability of fostering and maintaining the proper technical competence, a group of Army and Signal Corps personnel[3] decided to relieve a small percentage

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

[1] L. V. Berkner, "Government sponsorship of scientific research," *Science*, vol. 129, pp. 817–821; March 27, 1959.

[2] H. A. Zahl and E. M. Reilley, "Exploratory research," *Physics Today*, vol. 11, pp. 20–22; August, 1958.

[3] Dr. W. H. Martin, formerly Director of R&D, Dept. of the Army; Lt. Gen. J. D. O'Connell (Ret.), formerly Chief Signal Officer; Maj. Gen. Earle F. Cook, Deputy Chief Signal Officer (formerly Commanding General, USASRDL); Dr. H. A. Zahl, Director of Research, USASRDL; and Dr. E. M. Reilley, Director, Institute for Exploratory Research, USASRDL.

of the USASRDL scientific staff of responsibilities inherent in directed applied-research programs, crash developments of military equipment, and problems of contract administration. This decision culminated in the establishment of the exploratory-research program at USASRDL about $2\frac{1}{2}$ years ago.

Exploratory research, as conceived at USASRDL, is neither entirely basic research nor applied research, nor is it a compromise between the two, in its usual connotation. Definitions of basic and of applied research are legion, although customarily the former is characterized as general and fundamental, whereas the latter is considered to be practical and vocational. The concept of exploratory research does not exclude the gray areas that lie between basic and applied research; on the contrary, full recognition is given to an overlap between the two. The new concept encompasses the prosecution of basic research that is peculiar to the mission of the Signal Corps, as well as that degree of applied research required to show the need for military exploitation through additional research and development. Stated differently, exploratory research at USASRDL covers those investigations that are aimed at evolving fundamental data and concepts from poorly understood phenomena and properties of matter, and although the studies may have no *immediate* use, they may eventually lead to military application. In organizing the new program, the planners stressed the fact that exploratory research should supplement other parts of the Signal Corps research effort, and should supply the basic ideas on which future applied research and advanced developments could be logically planned. Implementation of the new ideas resulted in the establishment of a new organization at USASRDL—an Institute for Exploratory Research—wherein gifted scientists would be afforded the opportunity of conducting research in an environment conducive to such work.

The Institute comprises four operating divisions, each of which specializes in certain areas of the over-all exploratory-research effort. Coordination of the Institute's scientific programs is vested in an Exploratory Research Council, which consists of the Institute Directorate as Chairman and Deputy Chairman, the four exploratory-research division directors, and a representative from each of the other USASRDL departments. The Council is also responsible for integration of the Institute research program with applied-research programs throughout USASRDL. Uppermost among the aims of the Council are the following: 1) the establishment of long-range policy concerning scientific areas of potential importance and need; 2) the development of an environment favorable for the conduct of research; 3) the coordination and review of the scientific program of the Institute; and 4) the effective integration of the results of exploratory research into the appropriate applied-research and advanced-development programs of USASRDL.

Research programs in industry are being carried on in a plethora of scientific fields. Certain of these programs are conducted on such a large scale, and are so well manned and heavily supported, that token participation on our part would have been insignificant compared to that of other research organizations. Accordingly, Institute scientists interested themselves primarily in new fields of science—fields that had begun to be developed well after the close of World War II. From this basic philosophy of exploring new areas in science, we developed a program that includes studies in solid-state physics, plasma physics, nuclear physics, ionospheric physics, geophysics, mathematics and communications.

Solid-state physics may be described in general as that area dealing with investigation into and use of the electric, magnetic, and photic properties of solids. Although science has long recognized that special effects can be produced in some materials when energized by electricity, magnetism, or light, only recently has progress been made in the understanding of solids in their application to electronics. A summary of solid-state electronics developments to 1955 can be found in the special solid-state issue of PROCEEDINGS.[4] A major impetus was given to research in solid-state physics by the announcement of the transistor by Bell Telephone Laboratories, in 1948. This milestone in electronic progress and its impact upon communications technology have spurred studies in crystals and their properties, semiconductors, photoconductors, electroluminescent materials, and ferrites. Fruits of these labors have already been borne in military electronics equipments of all kinds: combat radios, field telephones, satellite instrumentation, and computers, to mention a few. The Institute's solid-state program currently includes studies on: electrical and magnetic properties of materials at extremely low temperatures; crystals and their growth;[5] energy transitions;[6] charge-transport phenomena and optical properties of semiconductors, ionic conductors, and superconductors;[7] new ferromagnetic, ferroelectric, and semiconductor materials;[8] effects of superpressure and high temperatures on known materials;[9] synthesis of new materials by superpressure-high temperature techniques; and improvement of presently known electronic materials. Progress has been made in all of this

[4] Solid-State Electronics Issue, PROC. IRE, vol. 43; December, 1955.

[5] P. Bramhall, G. K. Gaulé, and G. A. Wolff, "Growth of Single Crystals for Solid-State Application," presented at Army Science Conf., West Point, N. Y.; June, 1959.

[6] H. H. Theissing, P. Caplan, F. Dieter, and N. Rabbiner, "Optical pumping in crystals," *Phys. Rev. Letters*, vol. 3, p. 12; November 15, 1959.

[7] G. K. Gaulé, J. T. Breslin, J. R. Pastore, C. Pochop, and R. A. Shuttleworth, "Some Optical and Electrical Properties of Crystalline Boron," presented at the Electrochemical Society Meeting, Columbus, Ohio; October, 1959.

[8] J. A. Kohn, G. K. Gaulé, and A. A. Giardini, "High-Temperature Semiconducting Materials: Boron and Aluminum Borides," presented at Army Science Conf., West Point, N. Y.; June, 1959.

[9] A. A. Giardini and J. E. Tydings, "High-Pressure High-Temperature Research and New Electronics Materials," presented at the Electronic Components Conf., Philadelphia, Pa.; May, 1959.

work.[10,11] USASRDL has successfully demonstrated amplification and oscillation in an experimental three-level solid-state maser. We have outfitted a low-temperature laboratory and are about to initiate experimental work that will enable us to study properties of materials at temperatures below 1/10 of a degree absolute (−272.9°C). The superpressure program has resulted in the synthesis of diamond. A number of new magnetic materials have been prepared, and we have investigated the relationship between their crystal chemistry and electric-magnetic properties. Crystals have been synthesized and grown by a number of methods and techniques.

Nuclear physics studies at the Institute embrace a number of specific problems; *viz*, secondary-electron dosimetry, nuclear irradiations and calibrations, and effects of ionizing radiation on pyridine. As a result of experimentation on neutron dosimetry, our scientists have designed and built experimental models of a new-type dosimeter, which they named SEMIRAD (secondary-electron mixed-radiation dosimeter).[12] The SEMIRAD technique depends upon the collection and measurement of secondary electrons that are released from materials upon high-energy irradiation. In essence, the new device consists of two oppositely charged electrodes in a vacuum. The electrodes may be of either metal-coated hydrogenous plastic or other conducting material. When the device is irradiated with neutron and/or gamma radiation, high-energy Compton electrons and photoelectrons emerge from the electrodes, releasing low-energy secondary electrons. These secondary electrons are then collected at the positive electrode, the collection current being directly proportional to the radiation dose rate, and the total electron charge being proportional to the total dose. Unlike conventional ion-chamber dosimeters, SEMIRAD instruments are capable of measuring extremely high dose rates delivered in very short times. Recently, SEMIRAD devices have been tested successfully under a number of man-made nuclear environments: Godiva, Kewb, Triga, and Linac.[13] In addition, the Institute maintains a nuclear irradiation and calibration facility as a testing service for all USASRDL organizations that require such tests on components and equipments. The research teams also use this facility in connection with their nuclear investigations. Nuclear research, in brief, promises to yield significant information about the effects of radiation on electronic materials,[14] and about dosimetry techniques that will permit us to measure higher mixed gamma-and-neutron dose rates than ever before.

Ionospheric research, which has played an important role in USASRDL's program for many years, is actively being pursued by the Institute. High-lighting this work is the investigation of ionospheric electron content by means of the moon-relay method.[15] The current emphasis on space communications has generated an urgent requirement for a thorough investigation of the medium in which space vehicles spend a good portion of their useful lives. This medium is the ionosphere, the electron content of which determines the magnitude of the various phenomena that affect radio waves in their passage through the ionosphere. These phenomena include refraction, absorption, retardation, scattering, and reflection. The ionospheric electron content varies diurnally, seasonally, and with the sunspot cycle, and is also subject to irregular variations caused by ionospheric storms and man-made disturbances (such as atomic explosions). To communicate efficiently with missiles and satellites, or to detect them, we must be able to predict optimum frequencies. This ability presupposes a complete, continuous knowledge of the ionospheric electron distribution. Heretofore, vertical sounding was the only method of mapping the electron-density profile of the ionosphere. Since this method allowed us to measure electron densities only up to the layer of maximum electron density, the ionosphere above this layer was not accessible to investigation.

Our scientists in the Institute have used a new method of applying the ionospheric Faraday effect for obtaining more information about the ionospheric electron content.[16,17] This effect is a change in the plane of polarization of an electromagnetic wave that passes through those regions of the ionosphere where an appreciable magnetic field exists. The measure of this effect is an index of the ionospheric electron content. Institute investigators have used this effect, in conjunction with the moon-relay technique, for measuring the integrated electron content of the ionosphere. Use of the new method has shown that the ratio of the number of electrons above the layer of maximum electron density to that below averages about 3 to 1. The work was conducted on 151 Mc, and mostly at night (because of high daytime interference levels caused by ignition noise from traffic). It is planned to conduct future investiga-

[10] G. A. Wolff, I. Adams, and J. W. Mellichamp, Electroluminescence of AlN," *Phys. Rev.*, vol. 114, pp. 1262–1264; June, 1959.

[11] M. Green, "Space charge in semiconductors resulting from low-level injection," *J. Appl. Phys.*, vol. 30, p. 774; May, 1959.

[12] S. Kronenberg and H. Murphy, "USASRDL SEMIRAD Research," presented at Army Science Conf., West Point, N. Y.; June, 1959.

[13] S. Kronenberg and H. Murphy, "Irradiation of SEMIRAD at the General Atomic Linear Accelerator (LINAC), May 5, 1959," USASRDL, Fort Monmouth, N. J., Tech. Rept. 2070; September 1, 1959.

[14] C. Accardo, H. Hendel, R. Lauttman, and M. Stein, "Induced antimony activation in mylar," *Nucleonics*, vol. 17, p. 106; September, 1959.

[15] S. J. Bauer and F. B. Daniels, "Measurements of the ionospheric electron content by the lunar radio technique," *J. Geophys. Res.*, vol. 64, pp. 1371–1376; October, 1959.

[16] S. J. Bauer, and F. B. Daniels, "Measurement of the ionospheric Faraday effect by radio waves reflected from the moon," *Nature*, vol. 181, pp. 1392–1393; May 17, 1958.

[17] F. B. Daniels and S. J. Bauer, "The ionospheric Faraday effect and its applications," *J. Franklin Inst.*, vol. 267, pp. 187–200; March, 1959.

tions along these lines in noise-free locations, in order to enable observation of daytime variations in ionospheric electron content. In addition, transmissions on a different frequency (413 Mc) will be made for the elimination of a certain ambiguity in the results. A mobile station will be used to furnish important information about latitude variation in ionospheric structure. The results obtained to date have already changed the theoretically assumed physical model of the ionosphere, and the new information is currently used by the National Bureau of Standards in providing estimates for missile firings at Cape Canaveral. An additional result has been the determination of ionospheric temperatures at the F_2 peak.[18]

A new theory has been developed regarding radar reflections from the moon. This theory, which leads to results different from those obtained at Jodrell Bank Experimental Station, takes into account the fluctuations in depth of the lunar surface, and results in new expressions for the autocorrelation function of the fading of lunar signals, the space correlation function at the earth's surface, and the angular power spectrum. Application of this theory is expected to provide new information regarding fine-scale lunar surface irregularities that are not visible in a telescope.[19]

For almost a century, scientists have recorded natural microvariations in the earth's magnetic field. Although the causes of these variations are not fully understood, they are believed to be due mainly to transient solar phenomena and their interaction with the ionosphere and exosphere. In 1958, Institute investigators postulated that, since the energy required to produce these microvariations is compatible with the energy content of relatively small terrestrial effects, the latter could possibly produce such micropulsations. Furthermore, since the energy of magnetic storms is of comparable order of magnitude with that of large atomic explosions, it was considered possible that man-made events of this sort might cause magnetic disturbances of the magnitude of micropulsations. It was also reasoned that the interactions between the fireball and the earth's magnetic field should produce hydromagnetic waves that would propagate globally. Acting on these assumptions, the Institute's geomagnetic-research team instrumented two recording stations, one in Arizona and one in New Jersey. The magnetometers used were very large wire loops (about 100-square kilometers) laid out on the ground, and designed for very high sensitivity, low noise level, and very good time resolution. (A variation of 10^{-8} gauss/second induced a voltage of 0.1 millivolt in our loops.) During the 1958 Argus experiments, our stations recorded two signals from the explosion: a fast one, which arrived with a travel time of about four seconds, and a slow one, which arrived about four to five times later than the fast signal. Similar signals were recorded by other agencies on a world-wide basis at stations in Sweden, Iceland, the Azores, France, and Algeria.[20,21,22] Thus our geomagnetic team was in possession of accurate times of arrival of man-made magnetic signals that had propagated on a global basis. The data were then analyzed and compared with theoretical considerations concerning the propagation of hydromagnetic waves. This study led to an important conclusion, namely: the hydromagnetic waves caused by Argus were confined in a ductlike concentric shell about the earth, at a height of about 2500 kilometers. This duct is at a height where hydromagnetic waves travel with the greatest possible speed; that is, the waves tend to get into the fastest lane and use it for as long a time as possible to reach their destination. This phenomenon agrees with the Fermat principle, which states that a ray tends to travel along a path that can be followed in the least time. Future studies along these lines should yield more information about magnetic storms, world-wide radio fadeouts, auroral effects, and the magneto-electric properties of outer space.

Re-examination of earlier ionospheric records made during and after low-level atomic explosions has provided an explanation of the double arrivals of the shock wave in the ionosphere. No explanation of this phenomenon had been found previously. The additional arrival has been explained as a hydromagnetic shock wave that travels in the lower ionosphere with a velocity of about 50 per cent above that of an ordinary shock wave.[23]

One of the newer fields being studied by the Institute is that of plasma physics. Plasmas may be defined as quasi-neutral ionized matter, or matter that contains nearly equal numbers of positive ions and electrons. Natural plasmas exist throughout most of the universe, including the ionosphere and the interior of the sun and the stars, whereas man-made plasmas are generated in gas discharges and in atomic explosions. Plasmas exhibit many properties that are different from those of ordinary solids, liquids, and gases—in fact, plasmas have been considered to be a fourth state of matter. Research in plasma physics should enable us ultimately to simulate hydromagnetic phenomena occurring in the ionos-

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phere and the effects of atomic bursts. Results of this work will help us to improve communications systems used in ballistic missiles and space weapons, and to gain additional insight into the thermonuclear reaction. Based on these considerations, our plasma team has designed and constructed a high-energy plasma generator with a 100,000-joule storage capacity[24] and a time constant of less than one microsecond. Our principal concern has been with the interaction between radio waves and plasmas. Experiments have been conducted and some interesting microwave measurements have been made, *e.g.*, the transmitted and reflected phases and amplitudes of the microwave power, and the complex dielectric constant as a function of time.[25,26] Future work in this field will enable us to learn more about radiation phenomena, wave-propagation anomalies, and various effects of high-altitude explosions.

Experiences with radio and wire networks during World War II pointed out the need for more thoroughly integrated communications systems. In addition, rapid progress and changes in modern warfare methods have dictated the pursuit of a comprehensive research program aimed at obtaining new knowledge of communications techniques. Accordingly, the Institute is actively engaged in studies in the fields of radio and wire communications with specific emphasis on problems applicable to Department of the Army communications systems. The broad objective of these studies is to obtain new knowledge of transmission of intelligence and to arrive at a simplified system for all communications. These current studies include: investigation of basic aspects and new concepts concerning antennas, transmission lines, and associated networks;[27,28] study of theory of electromagnetic wavebeams to determine principal limitations of electromagnetic-power transmission through space;[29] investigation of radio transmissions by use of artificial electron clouds; determination of the best utilization of radar-terrain backscatter information in establishing UHF and SHF communication links;[30] investigation of new types of receiving theories and methods; and others. Some of the specific items under study are a center-fed vehicular antenna, a tapered-horn aperture antenna (TAHA), a circularly polarized rhombic antenna for use in satellite tracking, and a millimeter microphone for sensing atmospheric-density changes. Important findings have already resulted from this work. The feasibility of the center-fed vehicular antenna has been established and design principles have been formulated. The satellite-tracking antenna has been designed and constructed and is to be tested this year. Our scientists have constructed a millimeter equipment suitable for local loop communications. Results of artificial cloud experiments indicate that such clouds could be used to extend radio communications. Path-transmission-loss measurements were made at representative frequencies, and techniques have been developed for rapid path-evaluation recommendation. Institute scientists will continue in these areas to explore new possibilities for improving the military communications state-of-the-art.

The Institute also conducts a research program in mathematics aimed at investigating such areas as ordinary and partial differential equations, statistical mechanics, transcendental equations in electromagnetic theory, difference equations, switching theory and techniques, and information theory. The last item, a relatively new field, has potentially broad application to future Signal Corps developments, since it is becoming the formal science treating detection and identification of signals of all types. From this field may emerge new practical methods for compressing bandwidth, for reducing transmission errors, for improving message security, and for improving transmission or detection range by multiple correlation. The Mathematics Division of the Institute also maintains a computational facility that uses a Burroughs Datatron 220 high-speed electronic computer to obtain solutions to a variety of scientific and engineering problems for all of the USASRDL organizations.

This article was prepared to furnish the reader with a general overview of the Institute for Exploratory Research, its basic philosophy, its programs, and some of its progress. In the short time since its conception, the Institute has demonstrated that a policy of stimulating creativity and the generation of ideas in an environment of normal military urgency is both workable and profitable. The Institute aims to continue its policy of stimulating creativity and the generation of ideas. To borrow a phrase from Dr. Ralph B. Winn, in his address at the Fort Monmouth Commandant's Guest Speaker Program, March, 1960, "This country, along with having the biggest business, the most advanced technologies, and the most food, should also be a country of creators, philosophers, and thinkers." The Institute has provided an atmosphere considered necessary to insure an adequate and well-coordinated research effort. We agree that new ideas are essential to future scientific progress, and we rededicate ourselves to the pursuit of new basic knowledge.

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Signal Corps Studies of Nuclear Radiation Effects on Electronic Components and Materials*

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Summary—The U. S. Army Signal Research and Development Laboratory has long been interested in the effects of nuclear radiation on electronic components and materials. An historical account of USASRDL participation in earlier weapons tests is presented along with more recent efforts toward the evaluation of component operation during a burst of nuclear radiation using various pulsed reactor facilities. The radiation effects on some present-day components is briefly described, and possible directions of future efforts to develop radiation-resistant components and equipment are proposed.

Introduction

THE introduction of nuclear energy to the world accompanied the use of a nuclear device as a weapon of war. This introduced a new environment to the military tactician. Prior to the conclusion of World War II, the military tactician had to consider only the conventional environmental effects of weapons, such as blast, shock and heat. Almost overnight, the nuclear weapon presented him with a new, little understood, field environment which became a hazard to his personnel and equipment.

The Army Signal Corps has long been responsible for development, introduction, and successful and efficient operation of most military field electronic equipment. Experience has shown that the hardening of electronic equipment to any environment first requires that information be obtained concerning the effects of these environments on the individual electronic components. This is then followed by the hardening of the piece parts, and finally, the improvement of the resistance of the complete equipment to the same stress. As the military tactician was faced with the new environment of nuclear radiation, the Signal Corps was faced with the problems of research and development attendant upon the introduction of successfully operated equipment for use in this same environment. The studies of nuclear radiation effects have, to date, concentrated on individual components and materials. It is the purpose of this article to summarize the history and accomplishments of the Signal Corps program aimed toward the development of nuclear radiation resistant electronics.

The original objectives of this program were outlined as follows:

1) To determine by field study at nuclear weapons tests the susceptibility of electronic piece parts to the nuclear radiation environment.
2) To reproduce and correlate these field results with studies using laboratory simulation-type facilities for the exposure source.
3) To determine the failure mechanisms and develop means for the hardening of the electronic piece parts to the nuclear environment.
4) To develop electronic piece parts which can withstand the nuclear environments experienced by field equipments beyond the range of destruction caused by blast and thermal effects of nuclear weapons.

Early Weapons Tests

Initial studies of nuclear radiation effects on electronic component parts emerged from some of the early weapons tests. Examinations for radiation damage were made on electronic components which had been stripped from various pieces of equipment exposed to these early nuclear bursts. However, physical damage, and the long storage time required for "cooling-off," made it impossible to detect any effects that could be attributed directly to nuclear radiation.

Later weapons tests saw the introduction of more sophisticated planned experiments directed at a determination of effects on individual components. Capacitors, resistors, vacuum tubes, solar cells, quartz crystals, semiconductor devices, and various materials used in electronic equipment, were exposed to different levels of radiation in such a way that they were protected from the thermal and blast effects of the nuclear burst. This arrangement of components permitted them to receive a relatively high dose of nuclear radiation without suffering any physical damage [1]. The devices were recovered from the test site, and the post-test electrical characteristics were compared with pretest values. Serious permanent radiation damage was apparent in the semiconducting and photosensitive devices. Minor damage was exhibited by the darkening of some glass tube envelopes and glass meter windows, and by degradations in some of the dielectric materials exposed.

Transient Effects Studies

These early studies provided information concerning component susceptibility to permanent radiation damage. There was no indication that transient effects occurred. The Signal Corps first became aware of nuclear

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radiation pulse effects on operating components when other government agencies requested technical information and consultation on transient effects on components and materials used in their equipment. As the study of pulsed nuclear radiation damage progressed, it became apparent that transient effects, observable on operating components during and immediately following the pulse, could constitute a major problem.

Preparations were made for a full scale, statistically valid, field study of transient effects caused by nuclear radiation from weapons tests. Recording equipment was procured, and the required associated electronics and test circuitry were designed and fabricated. Pre-weapons test tryouts of these systems were then conducted at the Los Alamos Scientific Laboratory's (LASL) Godiva II reactor (bare critical assembly; see Fig. 1).

The electronic test systems developed by the Signal Corps and its contractors consisted of high-speed, multichannel tape recorders, plus energizing, control and readout circuitry. The component parts under investigation were mounted on an exposure head which was placed as near as possible to the bare critical assembly (see Fig. 2). The circuitry and recording instrumentation was located at some distance from the Godiva reactor itself, and this equipment was operated remotely from a control room about a quarter of a mile distant [2]. Later experiments were performed in which tape recorders and associated circuitry were mounted in trucks or trailers. These vehicles were placed directly outside of the Kiva, the building in which the Godiva reactor is located. Further experiments employing oscilloscopes and photographic recording methods were carried out with the oscilloscopes located in the control room.

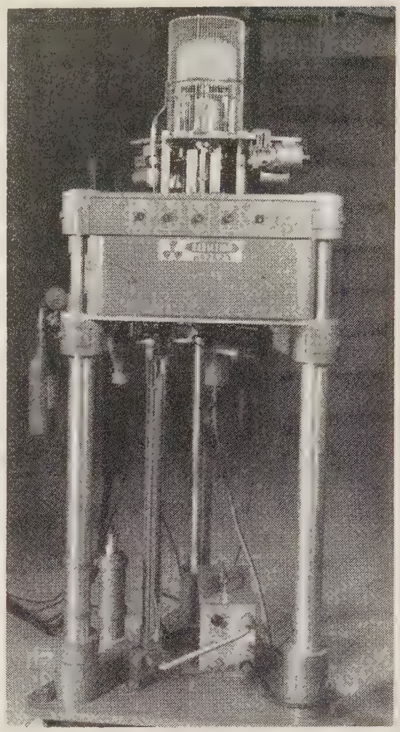

Fig. 1—Los Alamos Scientific Lab's Godiva II reactor. The Godiva II reactor is a bare critical assembly of approximately 58 kilograms of 93 per cent enriched Uranium 235. It is capable of delivering very short pulses of high intensity neutron and gamma radiation. Near the surface of the uranium assembly, a neutron pulse of about 10^{13} neutrons per square centimeter approximately 80 microseconds wide at half maximum may be obtained.

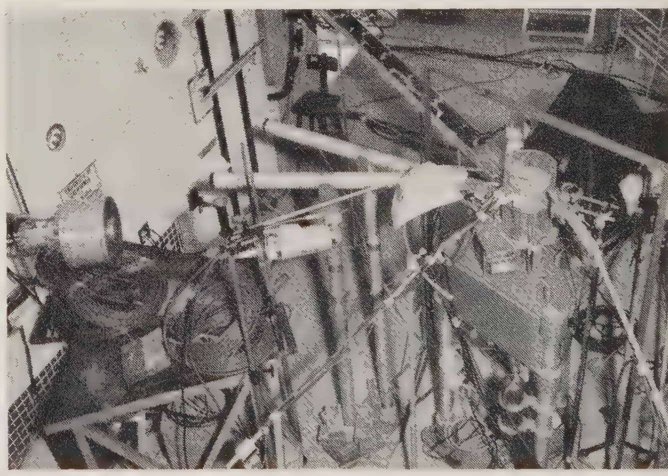

Fig. 2—Los Alamos Scientific Lab's., Godiva II reactor. View showing the various stands set up around the Godiva. These stands are holding the components and other devices at appropriate distances from the Godiva to give the exposure desired.

Examples of Data

Shown in Fig. 3 is the output of a ceramic pentode operating at 10 kc during a Godiva pulse. This output was recorded on high speed magnetic tape during the burst of the Godiva reactor, and then photographed later for study. Note that there is an interruption in the signal of approximately 500 microseconds, with the device completely recovering after 10 milliseconds and showing no permanent effects. The same type of tube, exposed at a distance of 100 centimeters and at a dose two orders of magnitude lower, showed no effect. The information sought, in this study, concerned the actual operating characteristics of the electron tube in the circuit; therefore, no correlation with specification data can be made until further statistical data are taken.

Pulse radiation effects on other prototype electron tubes showed various alterations in their ac outputs recovering within 8 to 20 milliseconds after exposure to a Godiva pulse. The elimination of tube sockets and changes of input time constant in the grid circuits indicated no significant changes in recovery time. An interesting side experiment revealed that a variable air-capacitor-oscillator experienced a complete blackout ranging from 45 milliseconds at 2 meters from the Godiva (or less than 10^{11} Nvt) to 30 milliseconds at 8 meters (or less than 10^{10} Nvt).

Fig. 4 illustrates the tape recording of the Godiva pulse effects on the I_{co} of four different germanium transistor devices [4]. The first, a thin based high-frequency device, which was least affected in previous steady-state reactor studies, exhibited no transient effects. The DAPT is a power transistor which exhibited serious

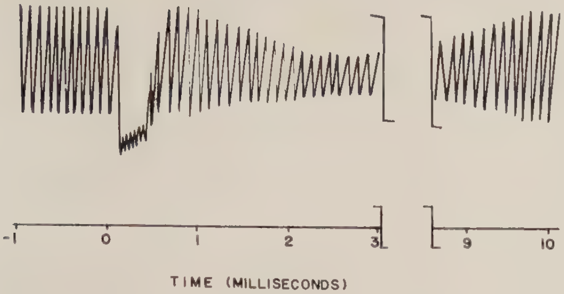

Fig. 3—The effect of a Godiva pulse on the ac output of a ceramic pentode.

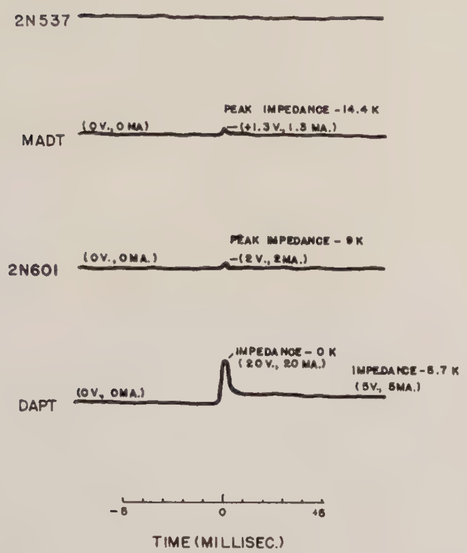

Fig. 4—Oscillograph recording of the Godiva pulse effect on the I_{co} of various transistor devices.

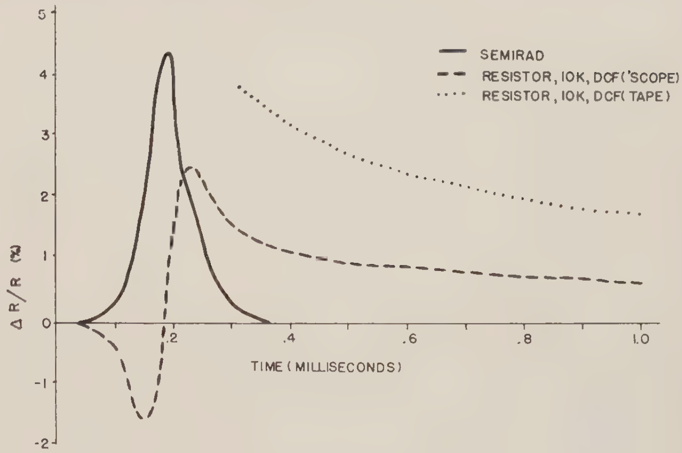

Fig. 5—The effect of a Godiva pulse on 10 K, deposited carbon film resistors.

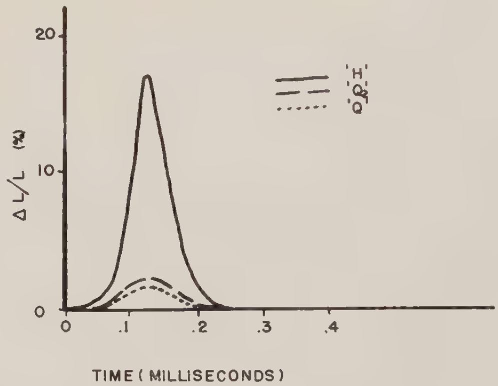

Fig. 6—The effect of a Godiva pulse on ferrite magnetic materials.

effects, as was expected. These are shown in the bottom curve. The two middle curves are on medium power transistors; the MADT is a development sample of a high power device being designed with radiation resistance a prime consideration.

Fig. 5 shows how, with the high resolution of oscilloscope and polaroid camera, an unusual effect on a 10 K deposited carbon film resistor has been captured [5]. First, there is a decrease in resistance resulting from the ionization. This is very quickly masked and counteracted by an increase in resistance, probably due to some solid-state lattice structure damage occurring in the resistive film. This latter effect quickly anneals out. The dotted trace showed what was seen on a previous experiment on a 10 K deposited carbon film resistor, using tape recorder techniques. The solid trace is that of the Godiva pulse itself, as detected by SEMIRAD (from the words "Secondary Electron Mixed Radiation Dosimeter"), a device developed by Signal Corps scientists which permits the measurement of high rate radiation pulses without saturation.

Fig. 6 shows the transient changes that were observed in magnetic ferrites exposed to Godiva [5]. It should be noted that these effects appear even at radiation doses several orders of magnitude lower than those at which permanent effects are observed in steady-state reactors. The Q and Q_2 ferrites showed only slight sensitivity with resultant increases of 2 to 3 per cent in permeability. However, the H ferrite, showed an increase of 17 per cent. In a tuned circuit this effect would cause a change in frequency greater than 4 per cent.

At the most recent Godiva experiment, dynamic transient-effect measurements were made on quartz crystal units for the first time [6]. Preliminary data reveal changes in frequency that lasted beyond the time of irradiation. A CR-56/U crystal unit, operated at 10 mc, underwent a 0.0085 per cent decrease (0.005 per cent tolerance) in frequency for at least 2.8 milliseconds after exposure to the Godiva neutron pulse. Now that suitable instrumentation techniques have been developed, experiments are in preparation to examine a number of different types of crystal units under pulsed irradiation.

These data, obtained by the Signal Corps, can be summarized as follows:

1) Nearly all components are affected to some degree during a high dose exposure to the Godiva pulse.

2) Components with a voltage potential across them appear to have a shunt resistance during the radiation pulse due to ionization.
3) Many components are affected for periods longer than the Godiva pulse period, and may take from milliseconds to seconds to return to their original state. Certain components were affected permanently; primarily semiconductor-type devices.

It is important to remember that these effects may be serious only in certain applications, but, for that reason, it is imperative that the length and magnitude of the transient radiation effects be known for those components which may be used in these applications.

Other Radiation Studies

As industry and government became more interested in the problem of radiation effects, and the weapons tests were postponed and finally cancelled, the Godiva II at LASL became increasingly difficult to obtain for test purposes. Among others, USASRDL began a search for other facilities that could be used as sources of pulsed radiation. Devices such as pulsed linear accelerators and nuclear reactors designed to go safely through a power excursion, can supply such a pulse. Two facilities were found that gave reasonable dose levels at the expense of the shorter pulse. These were the Kinetic Experiment on Water Boilers (KEWB) at Atomics International, and the reactor for Training, Research, and Isotopes of General Atomics (TRIGA). The pulse capabilities and other characteristics of these facilities are shown in Fig. 7. There are differences in spectra due to construction material differences. The Godiva, being a bare critical assembly, has a spectrum more nearly that of pure fission.

equivalent radiation doses. The duration of the effects observed were mutually consistent with the variations of pulse duration for each reactor. However, it should be noted that in the case of certain transistors, the effects followed the longer pulses of the TRIGA and KEWB reactors quite faithfully, whereas in the Godiva exposures there had been some lag in the recovery. This indicated that the recovery rates of some of the transient damage on solid-state devices are of the magnitude of the Godiva pulse rate, and therefore were masked on the TRIGA and KEWB time scales. It has been concluded that facilities such as the TRIGA and KEWB can be used for pulse radiation effects studies with the following limitations: 1) the longer pulse does not permit observation of annealing phenomena, 2) the neutron energy spectrum is somewhat degraded from the pure fission spectrum, 3) the exposure area is usually limited and 4) the over-all output does not represent the worst condition of radiation environments. At present, the Signal Corps requirements appear to be best satisfied by a Godiva-type facility.

Some limited experiments have been conducted using pulsed gamma and pulsed neutron linear accelerator devices. The data from these studies seem to indicate that the low total dose available from these instruments may be below the threshold at which large amounts of damage begin to occur. It appears that, unless the total output of such a device can be increased, the various types of linear accelerators will serve primarily as a means of conducting specific studies of a research nature rather than as a final test environment.

In addition to the pulsed irradiation work, other studies were conducted using steady-state reactors such as those at Brookhaven National Laboratory and at Curtiss-Wright's Quehanna Laboratory, as well as the Naval Research Laboratory's van der Graaf, and the Co^{60} source at Radiation Applications Inc. These studies have shown the radiation dose levels at which various components undergo permanent alteration in their electrical characteristics, and how those effects depend on the length of exposure. Recent studies have indicated that transient effects can be produced in electron tubes during exposure at high flux in steady-state reactors. The gamma irradiations made at RAI

	Fuel	Pulse Width at Half Maximum	Total Neutrons/cm² per pulse	
			Outer Surface	In core or "Glory Hole"
Godiva II	93 per cent enriched U^{235} metal	80 μsec	1.4×10^{13} fast c. 10^{10} therm.	1.0×10^{14} fast c. 10^{11} therm.
TRIGA	Zirconium hydride, U alloy	15 msec	c. 10^{13} fast c. 5×10^{14} therm.	7×10^{13} fast 3×10^{14} therm.
KEWB*	Uranyl sulfate solution	3 msec	c. 10^{14} total	

* This reactor has recently been modified; therefore, characteristics may be altered.

Fig. 7—Characteristics of some nuclear reactors capable of delivering short pulses of neutrons.

Various groups in USASRDL have conducted studies at the KEWB and TRIGA reactors. The experiments were designed to investigate the feasibility of using these facilities as substitutes for the Godiva, and to obtain additional information on radiation damage on electronic components.

In general, the data obtained at TRIGA and KEWB were in agreement with what was expected, the results being qualitatively similar to the Godiva results for

were designed to demonstrate the effect that high intensity gamma fields from fallout might have on electronic parts and materials. One of the more significant results of this study is the effect on capacitors, *i.e.*, increase in leakage current.

From the above data, it has been determined that the ultimate objectives of the program for the development of radiation resistant electronics may be attained if the following concepts are employed: 1) the circuits may be redesigned electrically or repackaged physically so that nuclear radiation transient effects become negligible, 2) the susceptible components may be replaced by existing electronically equivalent but more radiation-resistant devices, or 3) radiation-resistant devices may have to be especially designed or developed to replace susceptible components.

Future Work

Plans are being made to expand the present program to the level of a full scale research and development program covering the following aspects:

1) A study of the basic mechanisms of the interaction of nuclear radiation with electronic materials, components, and electronic circuits.
2) A statistical evaluation of all component types to obtain "data-in-depth" for use in making reliable predictions regarding their nuclear radiation susceptibility.
3) The development of new electronic components and materials resistant to damage from nuclear radiation, as well as new packaging, protective techniques, and circuit design concepts for fabricating radiation-resistant circuit functions.

These various phases are being supported by acquisition of additional radiation facility time, and inclusion of radiation specifications in component development work.

Although it has been long neglected, the problem of pulsed nuclear radiation effects on operating electronics is now being approached in a logical manner. It is expected that, in the future, this program should provide the U. S. Armed Forces with the radiation-resistant electronic equipment necessary for operation in the new environment, nuclear radiation.

Acknowledgment

The USASRDL program on radiation effects on electronic components is being conducted primarily by the Electronic Components Research Department. The authors listed in the references are just a few of the engineers and scientists of the various groups and contractors involved in this project. Support has also been received from other activities. The Institute for Exploratory Research, Division "S" has supplied the SEMIRAD dose-rate meter, personnel dosimetry, sulfur and gold dosimetry for neutron dose determination, and general technical assistance. The Atomics Branch of the Surveillance Department has supplied total gamma and neutron dose measurements from weapons tests, has helped in the preparation and evaluation of weapons test experiments, and was of valuable assistance in preparing for the field tests. Certain phases of this work have been done under the auspices of the Defense Atomic Support Agency, formerly Armed Forces Special Weapons Project.

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Precision Frequency Control for Military Applications*

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Summary—**The paper discusses progress made in the field of frequency control over the past years, with emphasis on the contributions of the U. S. Army Signal Corps. The entire field is reviewed, including piezoelectric resonators and devices using atomic and molecular spectral lines. Several accomplishments which are thought to be of special importance are discussed in greater detail. These subjects include, among others: Properties of synthetic quartz, aging prediction of crystal units, new methods of temperature compensation for crystal units, piezoelectric crystals for the VHF range, measurement methods for piezoelectric resonators, cesium-beam frequency standards, ammonia maser, and gas cell devices.**

I. Introduction

PRESENT frequency control requirements are satisfied by a wide variety of devices ranging in accuracy from 120×10^{-6} to 2×10^{-10}, and in long-term stability from 5×10^{-6} per month to no measurable long-term drift in the instance of newly developed atomic standards. These devices appear in many configurations, from the miniature ruggedized crystal unit with high stability and reliability under missile and space environments, the more intricate "high-precision" resonator in a liquid helium environment, to the atomic and molecular beam devices with their high intrinsic accuracies determined by natural constants.

This wide variety of devices is a consequence of the gradual evolution of more complex military requirements over the past two decades. Military communications, although still the principal consumer of quartz crystal units, is not the only application today. Navigation, meteorology, missile and satellite tracking, and other sometimes more sophisticated uses for these components place even more stringent requirements on frequency control. Today frequency control devices include quartz crystal units, tuning forks, magnetostriction units, piezoelectric ceramics, gas cells, masers, and atomic beam standards, to mention the most prominent.

Quartz crystal units have been used for some four decades as controlling elements for precision oscillators and in filters.[1,2] However, it was not until the mobilization leading to World War II and, particularly, the decision of the Signal Corps, in 1940, to use crystal control in its forward-area communications, that military demands placed a high premium on the "Quartz Crystal."[3] With this new demand, production requirements mushroomed from a rate of approximately 70,000 units per year (1940) to 29,000,000 in 1944. With the termination of the war, the military demand retarded, but precision frequency control for Signal applications became a constant requirement. However, the crystal frequency tolerance requirement of 200×10^{-6} for most tactical Signal equipment in World War II gave way to 50×10^{-6} during the Korean War, and now has been tightened to 20×10^{-6}. Yet, with the impending universal adoption of SSB communications, this tolerance must be reduced by two more orders of magnitude, to say nothing of the special noncommunication applications which have focused attention on the so-called "atomic standards."

II. Quartz Crystals

The large demand for precision quartz crystal units has stimulated the Signal Corps to take the lead in research and development in this field for the past 20 years. This program has ranged from an aggressive program in materials research, including the search for new piezoelectric minerals, synthesis of quartz and its substitutes, to the investigation of the resonator properties, causes of aging, study of new crystal orientations and modes of vibration, new measurement methods, and temperature control. Additionally, Signal Corps scientists have actively participated in IRE standardization activities, which have resulted in a Standard on measuring methods[4] and a Standard on the determination of the elastic, piezoelectric and dielectric constants.[5] These standards are particularly important, because they have brought order and system into the hitherto confused terminology on piezoelectric crystals.

A. Quartz Crystal Synthesis

The huge consumption of quartz during World War II, and the fact that its principal source was from outside North America, resulted in its classification as a strategic material. The annual consumption of quartz for frequency control purposes increased to 1,880,000

* Received by the PGMIL, July, 11, 1960.
† USASRDL, Fort Monmouth, N. J.

[1] W. G. Cady, "The piezoelectric resonator," Proc. IRE, vol. 10, pp. 83–114; April, 1922.

[2] K. S. Van Dyke, "The piezoelectric resonator and its equivalent network," Proc. IRE, vol. 16, pp. 742–764; June, 1928.

[3] D. Terrett, "The propulsion from limbo," in U. S. Army in World War II, The Technical Services, the Signal Corps: The Emergency. (To Dec. 1941)," U. S. Gov't Printing Office, Washington, D. C., pp. 181–182; 1956.

[4] "IRE standards on piezoelectric crystals—the piezo-electric vibrator: definitions and methods of measurement, 1957," Proc. IRE, vol. 45, pp. 353–358; March, 1957.

[5] "IRE standards on piezoelectric crystals: determination of the elastic, piezoelectric, and dielectric constants—the electro-mechanical coupling factor, 1958," Proc. IRE, vol. 46, pp. 765–778; April, 1958.

pounds in 1944.[6] This circumstance provided the stimulus for the Signal Corps R and D program in the synthesis of quartz.

Commencing in 1946, the Signal Corps promoted several parallel investigations with universities, commercial laboratories, and at Fort Monmouth. By 1953, a method of synthesis, the hydrothermal method, had proved economically practical, and crystals grown on *AT* cut seeds were obtained weighing more than 900 grams. The growth cycle took 120 days. Subsequent research with *X* cut seeds (often called *Y* bar seeds) and still later with *Z* cut plates have shown even more spectacular results. In a typical pilot plant study, six autoclaves produced 7365 *Y* bar crystals weighing 3222 pounds in one year, with an average yield per autoclave of 88 pounds each 40 days of operation.[6]

The methods of growing quartz by the hydrothermal process, while distinct in some detail in that different pressures, temperatures, and seeds are used, are markedly similar in principle. One method, employing a stationary vertical autoclave, operates as follows: source material consisting of pieces of Brazilian quartz is placed on the bottom of the autoclave, with appropriate seeds suspended in the upper section. The seeds, in this instance, are *Y* bars of approximately $\frac{1}{8}$ inch cross section and 7 inches in length. A 2-molar solution of Na_2CO_3 and water is added to the autoclave, and heat applied to its bottom. Thermal convection carries the dissolved source (feed) material to the cooler seed area, and growth results. A temperature of 450°C and pressure of 10,000 psi is used. Variations on the above method include higher pressures (upwards of 20,000 psi), NaOH solution in place of the Na_2CO_3, crystal seeds of different cuts, and rocking instead of stationary autoclaves.[6]

Fig. 1 illustrates the present state of the art of quartz synthesis. For most military applications, synthetic quartz is perfectly adequate; however, where very high Q resonators ($2–5\times10^6$) are required, such as in the ultra-precision frequency standards, natural quartz is preferable, since the Qs of high precision resonators fabricated from synthetic quartz are sometimes as much as 25 per cent lower than their counterparts made from natural quartz. The frequency-temperature characteristics are also slightly different. It is these circumstances, and the fact that the "man-tailored" material provides a useful tool for the basic study of the fundamental properties of quartz, that continuing research in quartz synthesis is still promoted by the Signal Corps.

B. Fundamental Properties

The basic properties of quartz, both natural and synthetic, have been under extensive study by the Signal

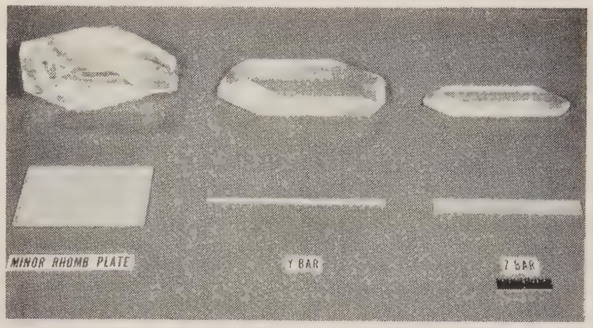

Fig. 1—Synthetic quartz grown from various seed plates. The seed plates are on the bottom, and the final crystals on the top.

Corps and other laboratories for some time. It has been found that synthetic quartz, while essentially similar to natural quartz, does differ in several respects. *AT*-cut quartz vibrators, carefully fabricated from natural and synthetic quartz, show a difference of 7 minutes in optimum orientation angle for large diameter to thickness ratios.[7] Optimum orientation is defined as that orientation of the crystal plate which gives the least frequency-change per unit temperature change.

The relationship between impurities in synthetic quartz and variation in their frequency-temperature characteristics has been a matter of great interest. Studies at USASRDL showed that aluminum doped synthetic quartz, fifth overtone, 29-Mc *AT*-cut resonators have higher inflection temperature and orientation angles than corresponding plates made from natural quartz having similar frequency-temperature characteristics. Inflection temperature is defined as that temperature at which the second derivative of frequency with respect to temperature is zero. In one experiment using aluminum-doped synthetic quartz, the inflection temperature was at 75°C whereas that of a corresponding resonator from natural quartz was at 20°C.[7,8]

Studies of the effects of X-ray irradiation on resonators cut from synthetic quartz showed that their frequency temperature characteristics can be modified significantly; furthermore, this effect can be removed by thermal bleaching at temperatures between 200 and 300°C for a few hours.[9]

[6] J. M. Stanley, "Signal Corps synthetic quartz program," this issue, p. 438.

[7] R. Bechmann, "The frequency-temperature behaviour of piezoelectric resonators made of natural and synthetic quartz," 1955 IRE Convention Record, pt. 9, pp. 56–61. Also see E. A. Gerber, "Temperature coefficient of AT cut quartz-crystal vibrators," Proc. IRE, vol. 43, p. 1529; October, 1955. A. R. Chi, "Some resonator properties of synthetic and doped synthetic quartz," 1956 IRE Convention Record, pt. 9, pp. 70–75. R. Bechmann, "Frequency temperature-angle characteristics of AT-type resonators made of natural and synthetic quartz," Proc. IRE, vol. 44, pp. 1600–1607; November, 1956.

[8] A. R. Chi, D. Hammond, and E. A. Gerber, "Effects of impurities on resonator properties of quartz," Proc. IRE, vol. 43, p. 1137; September, 1955.

[9] A. R. Chi, "Effects of X-ray irradiation on the frequency-temperature behavior of AT-cut quartz resonators," *Phys. Rev.*, vol. 107, pp. 1524–1529; September 15, 1957.

Under contract with the Signal Corps, scientists of Bell Telephone Laboratories have been investigating the anelastic processes induced by imperfections in the crystal lattice. In order to determine the internal friction, they carefully fabricated resonators from the material under study and measured the Q (quality factor) of the vibrating resonator at different temperatures down to 4.2°K. Interesting results have been observed. At 50°K, a strong relaxation absorption was found which was 3 orders of magnitude greater in some synthetic quartz than natural quartz, when using 5-Mc resonators. This is illustrated in Fig. 2.[10] The magnitude of the 50°K absorption is dependent on the crystallographic orientation of the seed plate upon which the quartz is grown. X-ray irradiation of synthetic quartz is found to minimize this loss at 50°K, but to induce a new small one at a higher temperature.[10,11] (See Fig. 3.)

Further work in this field yielded a method of electrolytic purification of synthetic quartz, wherein impurities are "swept out" by subjecting the sample to a static electric field at elevated temperatures. By this method, it was learned that the 100°K defect induced by X-ray irradiation was due to substitutional aluminum in the crystal lattice.[12]

C. Piezoelectric Resonators

Ever since the launching of an accelerated effort to develop precision crystal units, the Signal Corps has promoted research into a better understanding of the mechanism of the complete piezoelectric vibrators, in order to place the technology of crystal fabrication on a firm scientific basis. Activity dips over the temperature range, reduction of spurious modes in filter crystals, optimizing of dimensions of the crystal plate for maximum resonator performance, and improvement in frequency stability of the crystal unit under acceleration are typical of the problems presently being resolved under this program.

Under Signal Corps contract, Columbia University is conducting a mathematical analysis of the elasticity and vibration of crystalline bars and plates. The motion of piezoelectric crystals operating as mechanical resonators is enormously complex, and, since the material is anisotropic, evolving the mathematical solutions is indeed a formidable problem. To date, they have evolved solutions for the extensional vibration of circular quartz plates for four different crystal cuts; however, solutions to the more popular cuts such as the thickness and face shears have yet to be elicited.[13]

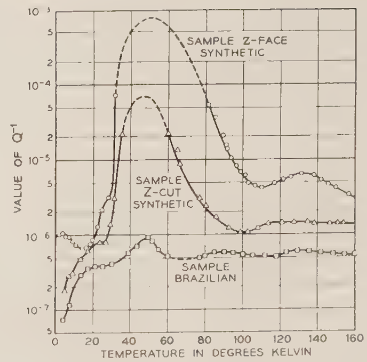

Fig. 2—Reciprocal quality factor Q of 5-Mc resonators fabricated from various quartz samples, as a function of temperature. (Courtesy J. C. King, Bell Telephone Laboratories)

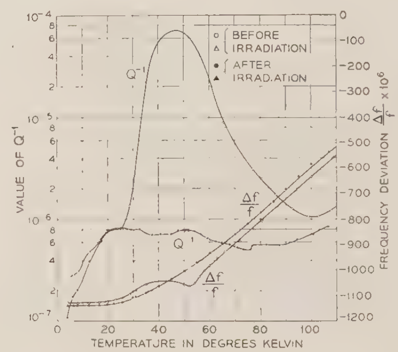

Fig. 3—Reciprocal quality factor Q and frequency deviation of 5-Mc resonators fabricated from synthetic quartz, as a function of temperatures, measured before and after irradiation. (Courtesy J. C. King, Bell Telephone Laboratories)

Fig. 4 illustrates the amplitude distribution of a vibrating flat, square quartz plate. This particular model shows the special case of a strong coupling between a thickness mode and a flexural mode. It is the result of measurements conducted at Wesleyan University wherein the piezoelectric charge on the surface of a quartz plate was measured as a function of the position of a probe electrode.[14] Other researchers[15] have carried on this work by experiments on fully plated, flat, circular AT-cut plates, in order to trace curves of frequency as a function of diameter. Other workers in the field, using a highly refined semiautomatic probe technique, have completed measurements on vibrating circular quartz resonators and shown mode and polarization patterns.[16] The unique feature of this apparatus is that the probe has a diameter of but 0.3 mm. This research, sponsored by USASRDL, is yielding a better insight into the complex problem of vibrating quartz crystals.

[10] J. C. King, "Effects of X-ray irradiation on the anelasticity of natural and synthetic quartz," *Proc. 12th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 85–100; May, 1958.

[11] J. C. King, "Anelasticity of synthetic crystalline quartz at low temperatures," *Phys. Rev.*, vol. 109, pp. 1552–1553; March 1, 1958.

[12] J. C. King, "Dislocation and impurity-induced defects in quartz," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 1–16; May, 1959.

[13] R. D. Mindlin, "Mathematical theory of vibration of elastic plates and bars," *Proc. 12th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 2–8; May, 1958.

[14] K. S. Van Dyke, "Strain patterns in thickness-shear resonators" *Proc. 11th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 41–61; May, 1957.

[15] C. R. Mingins, R. W. Perry, and D. W. MacLeod, "Frequency spectra in quartz resonators," *Proc. 12th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 10–36; May, 1958.

[16] I. Koga, H. Fukuyo, and J. E. Rhodes, "Modes of vibration of quartz-crystal resonators investigated by means of the probe method," *Proc. 13th Annual Symp. on Frequency Control.*, Asbury Park, N. J., pp. 54–70; May, 1959.

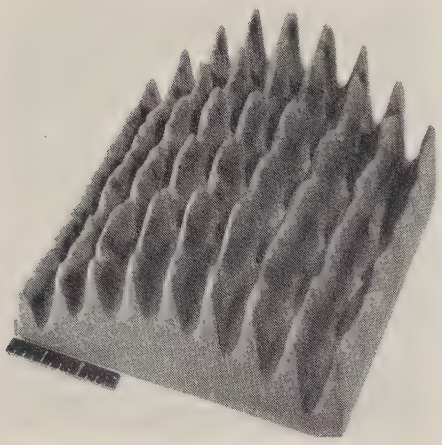

Fig. 4—Distribution of amplitude of a vibrating quartz plate measured with a small probe electrode. (Model by K. S. Van Dyke, Wesleyan University.)

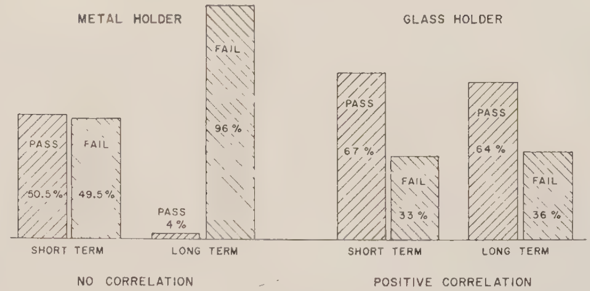

Fig. 5—Correlation of aging tests for metal and glass-enclosed quartz crystal units. (Short-term $=0.5\times10^{-6}$ per five days. Long-term $=5.0\times10^{-6}$ per six months.)

D. Aging

Aging is defined as the gradual change of frequency with time, all other variables assumed constant. This aging phenomenon has always been characteristic of crystals in varying degrees, and research toward a better understanding of its mechanism has been promoted by the Signal Corps for the past twenty years. Considerable progress has been made when one compares the aging rate of a current military type Crystal Unit CR-18/U, 5×10^{-6} per month with the aging rate of early World War II pressure mounted types, before the etching process for final finishing was introduced. These early units aged out of tolerance (200×10^{-6}), while in depot storage. Yet, as the aging rates are reduced, requirements for closer tolerance units seem to minimize this improvement.

The majority of today's military crystal units are plated, wire mounted resonators sealed in metal enclosures. Experimental units are being developed in glass holders. Aging studies on these two classes of crystal units, over the past several years at USASRDL[17] and Georgia Institute of Technology[18] are leading to a better understanding of this phenomenon and to better crystal designs with significantly lower and more predictable aging rates. One of the problems in writing specifications for military crystal units has been the stipulation of a reasonably short-term aging test which can be reliably used for predicting the long-term aging. Fig. 5 illustrates the radical difference in correlation between short- and long-term aging tests on metal enclosed crystals as compared to their counterparts mounted in glass holders. The criteria for passing the short-term test is a drift rate less than 0.5×10^{-6} per 5 days, and that for the long-term test, 5×10^{-6} per 6 months. Note the excellent correlation for the glass enclosed crystal units. Little correlation is observed for the units in metal holders. In addition, the units in metal holders show a significantly higher failure rate due to aging than do the glass-enclosed units. One cause of aging in present military crystals is now concluded to be a change in surface loading of the crystal plate by diffusion, adsorption or desorption of gases, corrosion, and recrystallization processes in the metal plating. Extremely small leaks in the metal container, especially in the soldered areas, are major contributors to the above.

The aging of high precision, high Q, crystal resonators is being studied, with considerable attention directed toward changes in the crystal lattice. Since it is known that the aging rates are lower as ambient temperatures are reduced, this phenomenon is being investigated at liquid helium and liquid nitrogen temperatures under Signal Corps sponsorship. At the National Bureau of Standards, 100-kc GT cut resonators were held at a 4.2°K temperature, and the long-term drift observed for more than a year. Random drift of a few parts in 10^{11} was measured, but the yearly average indicated little or no aging.[19] At Bell Telephone Laboratories, a 10-Mc *AT* cut, high Q resonator was subjected to a sustained temperature of 4.2°K, and a Q of 50×10^{6} was measured; essentially no aging was noted. Also, 2.5-Mc *AT* cut 30-mm-diameter resonators were operated at room temperature and demonstrated aging rates of approximately 10^{-10} per month.[20] Lower temperature operation of crystal units, in order to lessen the aging, has stimulated interest in Peltier effect cooling and other techniques.

E. Crystal Units

Present military crystal units are quite different from the units used during World War II. With only a few exceptions, all are now plated, wire mounted, and mounted in sealed containers; they are smaller in size and weight, have higher Q's and lower aging rates, oper-

[17] P. E. Muvilhill, "Aging characteristics of quartz-crystal units," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 109–122; May, 1959.

[18] R. B. Belser and W. H. Hicklin, "Stability studies of industrially and laboratory fabricated AT-cut quartz resonators of 16.25-Mc fundamental frequency," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 71–108; May, 1959.

[19] P. A. Simpson and A. H. Morgan, "Quartz-crystals at low temperatures," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 207–231; May, 1959.

[20] A. W. Warner, "Ultra-precise quartz-crystal frequency standards," IRE Transactions on Instrumentation, vol. I–7, pp. 185–188; December, 1958.

ate over a much wider frequency range; and most significantly, perhaps, is the fact that their electrical performance can be predicted with confidence. Fig. 6 contrasts typical present-day military crystal units with their counterparts of twenty years ago. Air-gap-mounted crystals in Holder FT-164 were the closest tolerance military crystals until the GT cut crystal was introduced for use in the Loran Frequency Standard about 1944. Present military high precision crystals are mounted in the T-5½ bulb illustrated.

Fig. 7 is a table illustrating some typical crystal units. It is not intended to enumerate an exhaustive list, there being more than 70 different types in existence at the present time. The trend in closer tolerance crystals may result in the adoption of crystals in glass holders for many applications.

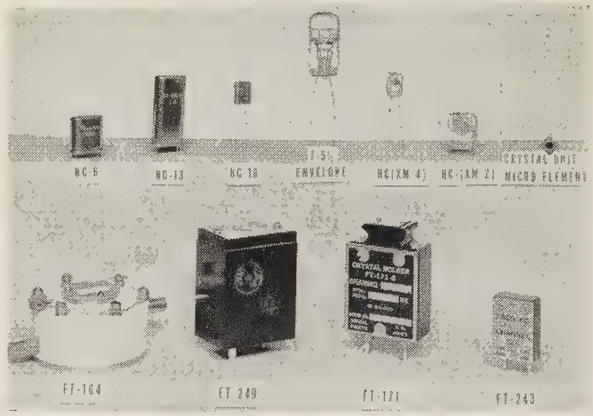

Fig. 6—Past and present-day crystal units.

Device	Frequency	Temperature Range	Accuracy*	Stability (With Respect to Time)	Q of Resonator	Space Requirement	Status
CR-18/U	0.8–20 Mc	−55° to +90°C	$\pm 50\times 10^{-6}$	5×10^{-6} per month	0.05×10^{6}	HC-6 Holder (Metal)	Production
CR-61/U	17–61 Mc	Oven Cont. Nominal 85°C	$\pm 20\times 10^{-6}$	5×10^{-6} per month	$0.1\ \times 10^{6}$	HC-18 Holder (Metal)	Production
CR-(XM-17)	0.8–20 Mc	Oven Cont. Nominal 85°C	$\pm 10\times 10^{-6}$	4×10^{-7} per month	0.25×10^{6}	HC-(XM-2) Holder (Glass)	Experimental
CR-(XM-18)	125–150 Mc	−55 to +105°C	$\pm 50\times 10^{-6}$	5×10^{-6} per month	$0.1\ \times 10^{6}$	HC-18 Holder (Metal)	Experimental
CR-71	5 Mc	+71 to +83°C** Oven Cont.	$\pm\ 1\times 10^{-6}$	3×10^{-8} per month	$2\ \times 10^{6}$	T-5 ½ Glass Bulb	Production
CR-( )	2.5 Mc	Oven Cont. Nominal 40°C	$\pm\ 1\times 10^{-6}$	2×10^{-10} per month 2×10^{-10} per second	$5\ \times 10^{6}$	T-11 Glass Bulb	Experimental

* Value given is manufacturer's tolerance for given temperature range.
** Oven temperature to be adjusted to the turning point of the crystal.

Fig. 7—Typical military quartz crystal units.

1) VHF Crystals: Considerable progress has been made in the upward extension of the frequency range of crystals since 1945. At that time, high frequency military crystals were operated only on their fundamental mode, with the upper frequency limit not much beyond 15 Mc, and the majority under 8.5 Mc. Today, overtone crystals as high as 150 Mc are becoming industrially feasible, and experimental crystals well above 250 Mc have been made. USASRDL has aggressively pioneered in the VHF field for quite some years, and with its introduction of the polishing process did much to demonstrate the practicability of VHF crystal control.[21] Fig. 8 illustrates the Signal Corps method of polishing by lapping with crystal plates "wrung" onto an optical flat. The parallelism of the plates is measured by an interferometer with a resolution of better than 0.000002 inch. The Signal Corps

Fig. 8—Polished-crystal plates wrung onto an optical flat (larger plate). A second optical flat with a smaller diameter is placed on top of the crystals, and its bottom surface forms interference fringes with the upper surface of the crystals.

[21] E. A. Gerber, "VHF crystal grinding," *Electronics*, vol. 27, pp. 161–163; March, 1954.

recently succeeded in lapping an AT cut crystal plate to a thickness of approximately 0.0005 inch, and, when mounted, it oscillated at a frequency of 123.040 Mc on its fundamental mode.[22] The equivalent network of a vibrating crystal is more complex at VHF than at lower frequencies since the reactive parameters of the crystal mount and holder become significant. Fig. 9 shows the equivalent circuit evolved at USASRDL, based on measurements of experimental VHF crystals.[23]

2) *High-Precision Crystals:* High precision crystal units are those which fall into a class with aging rates of less than 10^{-8} per week, grinding tolerance of 10^{-6} or less, and have Q's greater than 10^6. These crystals, formerly restricted chiefly for use in frequency standards, are now in demand for some forms of SSB communications, navigation, satellite beacons, and flywheels for atomic standards, to mention a few. These crystals are available industrially on only a few frequencies, 5 Mc being the most prominent. The present Signal Corps program is aimed at extending the range of available frequencies, improving the frequency stability under stress due to acceleration, reduction of aging, and investigating the short-term stability characteristics of the crystal oscillator over periods less than one second.

Results on long-term aging investigations have already been discussed in Section II-D. The short-time stability of a 5-Mc, high-precision crystal oscillator maintained in a liquid helium bath was measured by comparing it with an ammonia maser.[24] Fluctuations at time intervals as short as 0.001 second could be observed. Fig. 10 shows the relative stability between the maser and the crystal oscillator for the case of pressure regulation of the helium gas above the liquid, and without regulation. The average frequency change for one two-hour interval was less than 2×10^{-11} with pressure regulation. The rather large short-time frequency fluctuations, when pressure regulation is used, may be due to mechanical vibration of the regulator.[24]

High precision crystals for missile environments present additional problems. Employing a double convex plate, a stability of 2×10^{-10}/G or better under static acceleration for all orientations in the plane of the crystal plate, and 3×10^{-10}/G perpendicular to the plate has been achieved.[25] To withstand the high static accelerations encountered in missiles, the quartz plate must have a relatively small diameter to thickness ratio, in order to inhibit any slight bending of the plate.

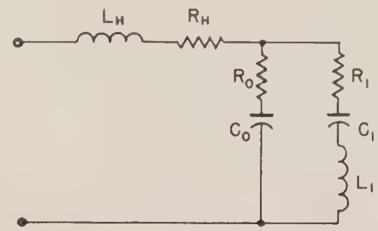

Fig. 9—Equivalent circuit of VHF crystal unit. Typical values of the parameters as found on experimental crystals units at 220 Mc are:

$L_H=15\times10^{-9}H$ $\quad R_1=35\Omega$
$R_H=5\Omega$ $\quad L_1=2\times10^{-3}H$
$R_0=1\Omega$ $\quad C_1=2.6\times10^{-16}F$
$C_0=6\times10^{-12}F$

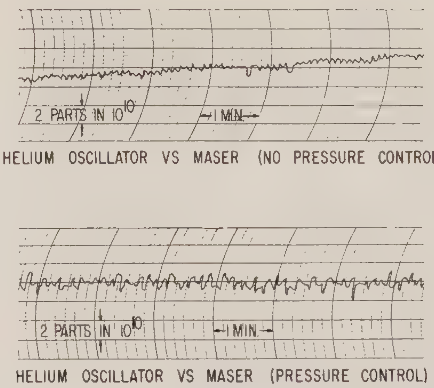

Fig. 10—Portion of a two-hour comparison between an ammonia maser and a liquid helium-cooled crystal oscillator. (Courtesy A. H. Morgan and J. A. Barnes, National Bureau of Standards.)

Using a different approach to the attainment of high stability, the excitation of AT cut thickness shear vibrators with an electric field parallel to the quartz plate is being investigated at USASRDL and in France.[26] The usual excitation of these plates is with a field perpendicular to the plate using electrodes covering the major surfaces. Preliminary results show that higher Q's can be obtained, probably due to a reduction of plating in the vibrational area. The possibility of lower aging rates with this method of excitation is probable.

3) *Close Tolerance Tactical Crystals:* New forward-area signal equipments require much closer over-all tolerances on frequency over wide temperature ranges than can be achieved with existing crystal cuts. Noting the sensitivity of the frequency of thickness-shear crystal resonators to external pressure,[27] a method of mount has been devised wherein bimetallic strips are applied to selected spots on the circumference of the crystal plate. The frequency-temperature behavior of the plate

[22] H. Wasshausen and W. Merkl, "New methods for preparation of high performance quartz-crystal resonators," to be published in the near future.

[23] E. Hafner, "A study of VHF crystal units," *Proc. 11th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 78–89; May, 1957.

[24] A. H. Morgan and J. A. Barnes, "Short-time stability of a quartz-crystal oscillator as measured with an ammonia maser," Proc. IRE, vol. 47, p. 1782; October, 1959.

[25] A. W. Warner and W. L. Smith, "Highly-stable crystal oscillators for missile applications," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 191–206; May, 1959.

[26] R. Bechmann, "Improved high-precision quartz oscillators using parallel field excitation," Proc. IRE, vol. 48, pp. 367–368; March, 1960.

[27] E. A. Gerber, "Precision frequency control for guided missiles," *Proc. First IRE Convention on Military Electronics*, Washington, D.C., pp. 91–98; June, 1957.

is thus modified so that the frequency excursion for a given temperature range is significantly reduced.[28] Fig. 11 shows the frequency change of an experimental model as a function of temperature for a typical plate with compensation by one bimetal strip. The position of the strip on the circumference of the plate, with respect to the Z' axis, is the parameter. The effect of the compensation is obvious. Fig. 12 is a schematic of one design employing two bimetallic strips, one compensating at the high temperature end of the range, and the other, the cold end.

Other avenues of approach to this same problem also being investigated by USASRDL include a search for new orientations for crystal plates, and use of the human body as a means for controlling the temperature of an oscillator employing specially oriented crystals.

4) Special Purpose Crystals: Crystal units for certain missile and satellite applications require a high degree of phase stability under vibration. It is apparent that vibration transmitted from the supports to the crystal resonator produce strains which induce frequency changes. Proper design of the mount can minimize the transmittal of vibration, and the choice of suitably stiff material for the mount will move its resonance frequency high enough so as to be out of the range of most vibration frequencies. Suitable orientation of the crystal plate with respect to the mount, so as to minimize the frequency change with stress, has made possible the fabrication of crystal units with stability as high as 10^{-10}/G in some instances. Fig. 13 illustrates the so-called "stiff mount" crystal unit developed at USASRDL and used in the Explorer Satellites and other applications. The more conventional spring mount used in most tactical crystals is illustrated in contrast.

A complete understanding of the mechanism of frequency and phase instability in crystal units as a function of acceleration, is still lacking, however. Experimental and analytical investigations are still being pursued by the Signal Corps, both at USASRDL[29] and under contract.

5) Filter Crystals: Recent developments in high frequency wide band crystal filters[30,31] have stimulated their adoption in the design of new military Signal equipment; and these successes have generated new requirements for crystal filters at VHF. One of the serious difficulties in the design of filter crystals for these networks is the presence of unwanted or spurious frequencies in the general neighborhood of the desired pass band. It has been found at USASRDL that these spurious frequencies can be substantially suppressed in high frequency fundamental mode plates by providing particular boundary conditions by means of special plate geometry and reduction of electrode size.[32,33] Fig. 14 shows two types of filter crystals, the one on the right being the triangular configuration. Fig 15 shows the mode spectrum of a conventional 11.5-Mc oscillator crystal, satisfactory for that application, but obviously impractical as a filter element. Fig. 16 shows the mode spectrum of a similar plate at 10.5 Mc, but with a triangular geometry and reduced plating area. The suppression of spurious frequencies by more than 50 db is

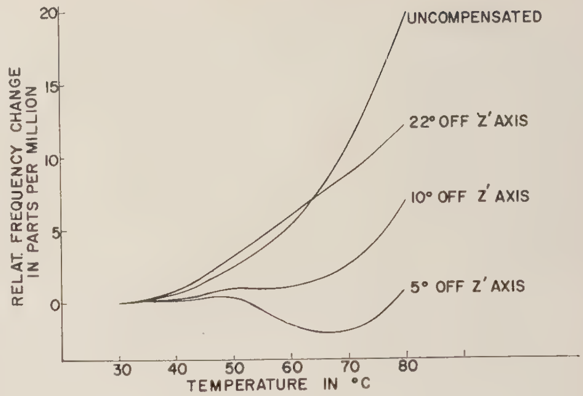

Fig. 11—Frequency change as a function of temperature for a bimetal-strip-compensated crystal unit. Parameter is the orientation of the contact point with respect to the crystallographic Z' axis.

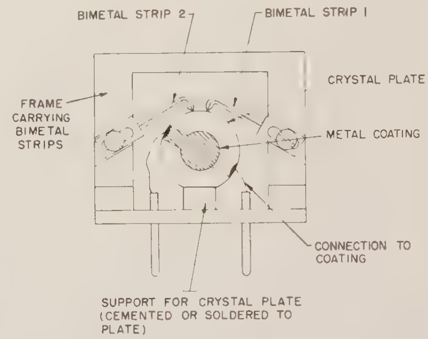

Fig. 12—Design of a crystal unit with two compensating bimetal strips.

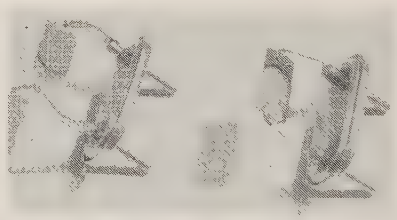

Fig. 13—"Stiff mount" crystal unit for missile application (left) and conventional spring mount (right).

[28] E. A. Gerber, "Reduction of frequency-temperature shift of piezoelectric crystals by application of temperature-dependent pressure," Proc. IRE, vol. 48, pp. 244–245; February, 1960.

[29] A. D. Ballato and R. Bechmann, "Effect of initial stress in vibrating-quartz plates," Proc. IRE, vol. 48, pp. 261–262; February, 1960.

[30] D. I. Kosowsky, "Crystal-filter design techniques and applications," 1957 WESCON Convention Record, pt. 6, pp. 94–107.

[31] R. A. Sykes, "A new approach to the design of high-frequency-crystal filters," 1958 IRE National Convention Record, pt. 2, pp. 18–29.

[32] R. Bechmann, "High-frequency quartz filter crystals," Proc. IRE, vol. 46, pp. 617–618; March, 1958.

[33] G. K. Guttwein, "High frequency crystal filters," *Proc. Symp. on Electromagnetic Interference*, Asbury Park, N. J., pp. 290–310; November, 1957.

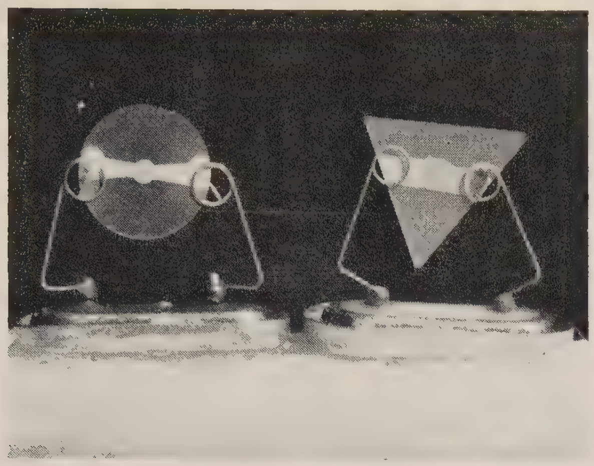

Fig. 14—Conventional crystal for filter applications (left) and triangular filter crystal (right).

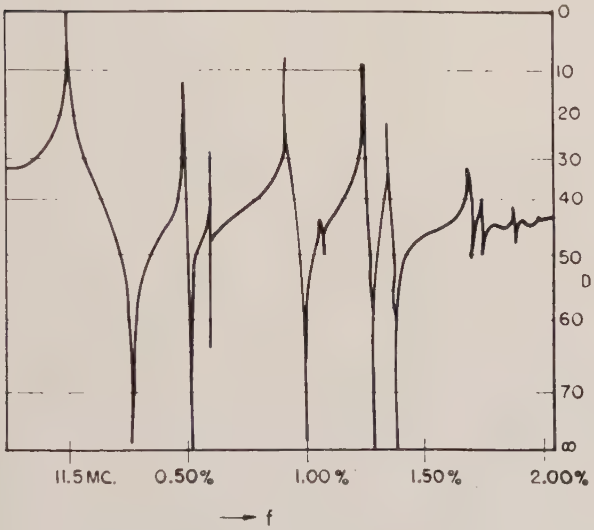

Fig. 15—Mode spectrum of an oscillator crystal.

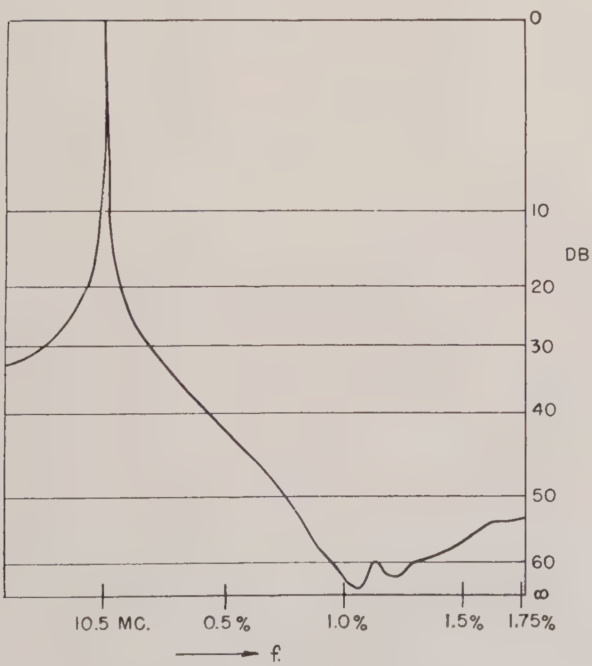

Fig. 16—Mode spectrum of triangular-filter crystal.

noted. This success has led to extension of these investigations to overtone mode filter plates at frequencies upwards of 60 Mc. To date, reduction of spurious modes in the VHF range has been experimentally verified only by preparing quartz plates with exceptionally small plated areas.

F. Quartz-Crystal Measurements

1) The Crystal-Impedance Meter: Before and during most of World War II, crystal units were tested in circuits reasonably identical with the oscillator circuits in which they were to be used. These test sets had to be accurately adjusted to correspond to the various oscillator circuits used in different radio sets. The adjustment had to be periodically checked against the corresponding primary standard-test sets. This procedure entailed a great deal of inconvenience and loss of time, without perfect assurance that the test set would retain its new calibration.

Therefore, it was a significant step forward when the Signal Corps Engineering Laboratories developed a series of test sets, which measured crystal units in terms of their fundamental electrical parameters by means of a substitution method.[34] The basic circuit diagram of a Crystal-Impedance Meter (CI-Meter) is given in Fig. 17. Several units have been developed which cover the frequency range from 2.5 kc to 200 Mc. The circuit employs a tuned grid-tuned plate arrangement with a crystal network in the main feedback path, which also contains a series capacitance C_T and variable substitution resistors. In operation, the crystal under test (with C_T short circuited for zero-reactance operation, and C_T in the circuit for positive-reactance operation) and the substitution resistor are alternately switched into the circuit, and the *LC* circuits and the value ofthe resistor are adjusted until the frequency and the grid current do not change when either the crystal or the resistor is in the circuit. Fig. 18 shows the front panel of CI-Meter TS-683/TSM covering the frequency range from 10 to 140 Mc.

Most of the test sets available at present exhibit an accuracy and a repeatability of setting of parts in 10^6. In the light of present-day requirements for crystal units with high precision, the above repeatability is not good enough. Work has, therefore, been underway to obtain a test set with an agreement between instruments of a part in 10^6 for accuracy, and a repeatability of setting to a part in 10^8. Recent investigations[35] have shown that the above goal is obtainable by close control of factors such as crystal current, substitution resistors, tube aging, and others. The use of a resistance-capacitance bridge in the feedback path also improves the repeatability.

[34] A. C. Prichard and M. Bernstein, "Crystal impedance meters replace test sets," *Electronics*, vol. 26, pp. 176–180; May, 1953.
[35] D. Pochmerski and C. L. Shibla, "Measurement of high-precision crystal units with increased accuracy," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 123–136; May, 1959.

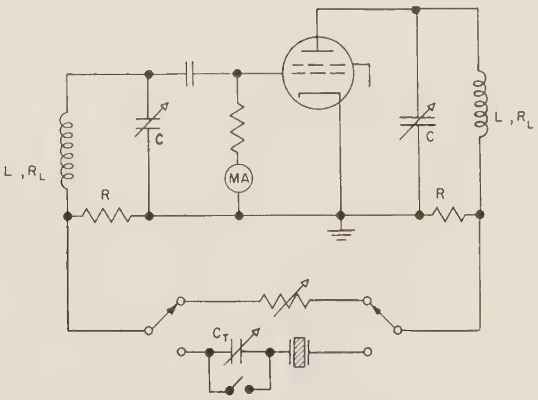

Fig. 17—Schematic of a crystal-impedance meter.

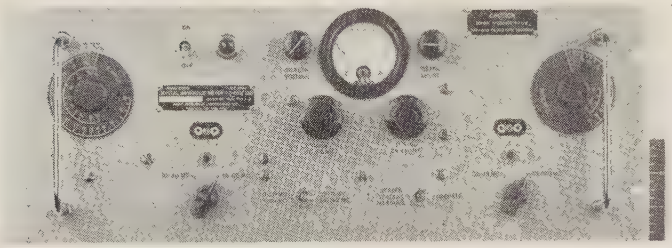

Fig. 18—Crystal-impedance meter TS-683/TSM.

2) *Other Methods for Measurement of the Equivalent Crystal Parameters:* Several other methods for crystal measurement have been investigated and utilized.[36] One of them, the so-called Transmission Circuit Method, has been standardized by IRE,[4] and recently adopted by the International Electrotechnical Commission (IEC) as an international standard, both with support from USASRDL personnel.[37] Fig. 19 illustrates the principle of the method. It consists of determining the frequency and the impedance at maximum transmission of a π network, in which the crystal unit under test is in the series branch. (The crystal is represented here by its equivalent circuit.) The frequency, at maximum transmission, is measured with and without a capacitance C_L in series with the crystal. From these measurements, the motional parameters of the crystal can be determined. In comparison with the CI-Meter, the transmission circuit is more a laboratory method; however, it is simple, convenient, and involves equipment normally available.

The measurement of quartz-crystal parameters presents an increasingly difficult problem as the frequency of operation increases much beyond 50 Mc. A bridge-type method has been developed by USASRDL for measurements in the VHF range, using commercially available VHF impedance bridges where the frequency

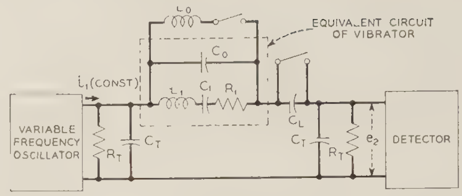

Fig. 19—Schematic of the transmission-circuit measuring method

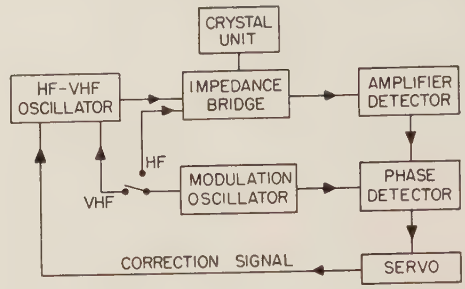

Fig. 20—Schematic of servo-controlled bridge test set.

of the test signal is automatically controlled to always keep the bridge balance to a minimum.[38] The principle of the method is illustrated in Fig. 20, which is self-explanatory. The switch enables one to select either frequency modulation of the oscillator or employment of reactance modulation in the bridge. The frequency range of this method depends upon the impedance bridge employed; measurements have been made on crystal units with frequencies as high as 300 Mc with a repeatability of a part in 10^8.

3) *Measurement of Unwanted Responses:* Oscillator reliability depends upon having crystals with only one mode capable of causing oscillation. There are two basic methods of detecting unwanted responses. The first consists of using a passive network incorporating the crystal to determine the amplitude and location of each unwanted mode, and then determining if any of these modes are harmful. The second and more direct method is to use the crystal in an oscillator whose ability to oscillate on unwanted modes can be adjusted and controlled to any desired degree. Two test sets were recently developed under Signal Corps contract, which were based on the latter method.[39] They cover the range from 1 to 125 Mc. The passive method, however, has the advantage of yielding the fundamental parameters of unwanted responses and, additionally, can be used to test filter crystals also. A test circuit, consisting of a simple bridge arrangement with hybrid transformer, is under consideration for military use.

[36] E. A. Gerber, "A review of methods for measuring the constants of piezoelectric vibrators," Proc. IRE, vol. 41, pp. 1103–1112; September, 1953.

[37] E. A. Gerber and L. F. Koerner, "Methods of measurement of the parameters of piezoelectric vibrators," Proc. IRE, vol. 46, pp. 1731–1737; October, 1958.

[38] E. Hafner, "A new method to simplify bridge-type measurements on quartz-crystal units," 1958 IRE National Convention Record, pt. 5, pp. 243–250.

[39] Joseph Loos, "An instrument for detecting unwanted modes in oscillator circuits," *Proc. 12th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 360–382; May, 1958.

Device	Frequency of Resonator	Accuracy	Stability (With Respect to Time)	Q of Resonator	Operational Time of Resonator	Space Requirement (With Frequency Translating Equipment)	Weight
Precision Crystal Oscillator (Commercially Available)	1 Mc	$\pm 1\times 10^{-6}$*	3×10^{-8} per month	1×10^{6}	Not Specified	$\frac{1}{3}$ cubic foot	20 pounds
Precision Crystal Oscillator (Experimental)	2.5 Mc	$\pm 1\times 10^{-6}$*	2×10^{-10} per month 2×10^{-10} per second	5×10^{6}	Not Specified	$\frac{1}{2}$ cubic foot	25 pounds
Cs-Beam Frequency Standard (Commercially Available Under the Name "Atomichron")	9193 Mc	$\pm 2\times 10^{-10}$	2×10^{-11} per day. However, No Measurable Long-Term Drift	60×10^{6}	10,000 Hours and Better	16 cubic feet	800 pounds (Commercial Model 1001)
						12 cubic feet	500 pounds (Military Model)
Ammonia Maser (Experimental, Portable, with Limited Coolant Supply)	23870 Mc	$\pm 1\times 10^{-9}$	1×10^{-11} per hour 2×10^{-10} per second	5×10^{6}	8 Hours	1 cubic foot	40 pounds
Gas-Cell (Rubidium 87, Experimental)	6835 Mc	$\pm 1\times 10^{-9}$	1×10^{-10} per month	300×10^{6}	Not Specified	$\frac{3}{4}$ cubic foot	30 pounds (Estimated)

* Crystal manufacturing tolerances only.

Fig. 21—Typical precision-frequency standards. The accuracy in the table presumes no prior adjustment of the device against a primary frequency standard. If this were done, the accuracy of the device would approach the resolution of the measurement equipment at the moment of adjustment.

III. Atomic and Molecular Resonance Devices

A. Comparison of Crystal and Atomic Frequency Standards, and Principles of Atomic and Molecular Devices

Considerable progress has been made in the improvement of the stability of quartz crystals, as pointed out in the preceding paragraphs. Data on crystal frequency standards are compiled in the first two lines of Fig. 21. The term "accuracy," as used in the table, is defined as the relative deviation from a previously accepted frequency value; "stability" is defined as the maximum relative frequency change during a specified time interval. It is noted that the aging rate of the experimental precision crystal oscillator, which was developed under Signal Corps sponsorship, has the extremely low value of 2×10^{-10} per month.[20]

Crystal standards, however, have the disadvantage of being secondary standards. The crystals must be lapped, and the oscillators adjusted to the desired frequency by means of comparison with a primary frequency standard. In systems, where a standard frequency must be reproducible at any time and at any place, or where the relationship between frequencies must be maintained very precisely over longer periods of time, a quartz standard usually will not meet the requirements. Fortunately, recent years have brought much progress in the utilization of atomic and molecular microwave spectral lines for frequency control purposes. The high invariance of their center frequencies, which are natural constants, and their very high Q-values, make some of these lines particularly attractive. Based on the work by Dicke, Kusch, Lyons, Zacharias and others,[40–45] the Signal Corps started a vigorous effort in 1955 to develop practical frequency standards employing microwave spectral lines useful for the defense effort.[46]

The frequency of any spectral line is proportional to the energy difference between certain discrete quantum states of an atom or molecule. This energy difference is either emitted or absorbed, depending upon whether the particle makes a transition to a lower (unexcited) or higher (excited) energy state, respectively. The probability for a transition is the same for either direction. Since a gas in thermal equilibrium contains more particles in the lower state of a transition than in the excited state, the net result will be absorption. This absorption line, however, will be weak, *i.e.*, its SNR low, because the population difference between two microwave states is very small at thermal equilibrium, ac-

[40] J. G. King and J. R. Zacharias, "Some new applications and techniques of molecular beams," in "Advances in Electronics and Electron Physics," Academic Press, Inc., New York, N. Y., pp. 1–88; 1956.

[41] N. F. Ramsey, "Molecular Beams," Clarendon Press, Oxford, Eng., 1956.

[42] J. P. Gordon, H. J. Zeiger, and C. H. Townes, "The maser—new type of microwave amplifier, frequency standard, and spectrometer," *Phys. Rev.*, vol. 99, pp. 1264–1274; August 15, 1955.

[43] K. Shimoda, T. C. Wang, and C. H. Townes, "Further aspects of the theory of the maser," *Phys. Rev.*, vol. 12, pp. 1308–1321; June 1, 1956.

[44] H. Lyons, "Spectral lines as frequency standards," *Ann. N. Y. Acad. Sci.*, vol. 55, pp. 831–871; November, 1952.

[45] W. B. Hawkins and R. H. Dicke, "The polarization of sodium atoms," *Phys. Rev.*, vol. 91, pp. 1008–1009; August 15, 1953.

[46] A very good account of the state of the art in 1955 is given by F. H. Reder in "Principles of Atomic Frequency Standards, A Non-Mathematical Discussion," Signal Corps Engrg. Lab., Fort Monmouth, N. J., Tech. Memo. 1671; April 25, 1955.

cording to Boltzmann's distribution law. Furthermoer, the line will not be infinitely sharp, the main reason for the broadening being the Doppler effect (assuming that the gas pressure is low). Most of the work in the past years has been directed toward an increase of the SNR by enhancing the population difference between two states, and toward a reduction of the line width by diminishing the Doppler and other line-broadening effects. Three different types of atomic and molecular frequency standards have evolved during the past few years: The cesium beam standard, the ammonia maser, and gas cell devices.

B. Cesium Beam Standard

In this device, the limiting factor for the sharpness of the line and, thus, for the Q, is the time τ which the atom or molecule has available for interaction with the microwave field, so that $Q=f/\Delta f \simeq f \times \tau$. The transit time, τ, depends upon the velocity of the particles in the beam and the length of the microwave cavity. The cesium beam standard uses a hyperfine transition between two particular energy states in Cs^{133} atoms, caused by the interaction between the magnetic moments of valence electron and nucleus. Fig. 22 shows the principle of a cesium beam standard.[46] A beam of Cs atoms is emitted from an oven and passes through an inhomogeneous magnetic field where the beam is split according to the states of the atom. Following the path of atoms in the lower energy state of the transition considered here, they pass through a cavity which is excited by an oscillator whose frequency is derived from a high-precision crystal. If the frequency of the oscillator is equal to the desired cesium transition of approximately 9193 Mc, then the atoms can absorb energy from the microwave field in the cavity, thus reversing their magnetic polarity so that they are deflected back to the axis during passage through the second magnetic field. The atoms will then hit a hot wire which ionizes the atoms. A correction voltage for the driving oscillator will be supplied if the number of atoms hitting the detector decreases, *i.e.*, if the frequency of the excitation field deviates from the atomic frequency. Fig. 23 shows two different types of cesium beam standards which have been developed by the National Company for the Air Force and Army, under Signal Corps sponsorship.[47,48] These are known by the tradename "Atomichron." The equipment on the right is the more recent and militarized version of the cesium beam standard.[49]

Recording the beat note between 2 standards for 72 hours resulted in a stability of 2×10^{-11}, according to Fig. 24. The circles represent averages taken over periods of approximately 40 minutes.[50] The two best Atomichrons were found to have deviated by no more than 1 microsecond after 63 hours or 5×10^{-12} of the measured time interval.[51] Atomichrons have been shipped by USASRDL to England, compared with British Cs standards of different design, and the prin-

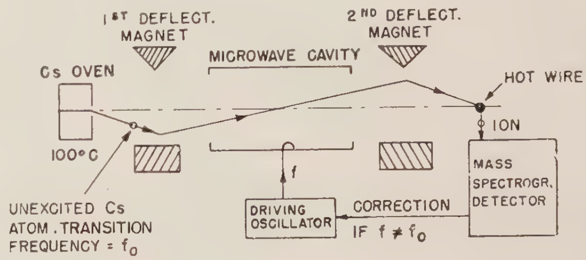

Fig. 22—Schematic of a cesium-beam standard.

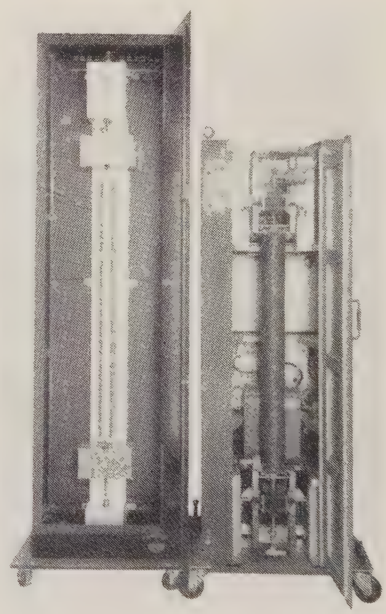

Fig. 23—Rear view of Atomichron (left) and militarized Atomichron (right), built by National Company.

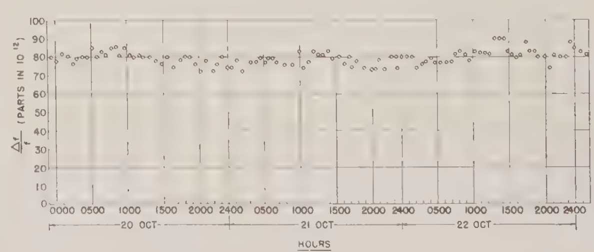

Fig. 24—Frequency stability of an Atomichron measured during a period of 72 hours.

[47] A. O. McCoubrey, "The Atomichron—an atomic frequency standard—physical foundation," 1958 IRE National Convention Record, pt. 1, pp. 10–13.

[48] W. Mainberger and A. Orenburg, "The Atomichron—operation and performance," 1958 IRE National Convention Record, pt. 1, pp. 14–18.

[49] A. O. McCoubrey, "National's militarized cesium-beam frequency standard," *Proc. 13th Ann. Symp. on Frequency Control*, Asbury Park, N. J., pp. 276–296; May, 1959.

[50] F. H. Reder and S. Roth, "Evaluation of a Cs-beam standard and frequency control division's future R and D plans," *Proc. 12th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 385–401; May, 1957.

[51] R. Bridgham, G. M. R. Winkler, and F. H. Reder, "Synchronized clock experiment," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 342–349; May, 1959.

cipal sources of error studied. There remains no unresolved discrepancy between the standards, within the limits of errors of observation.[52] Additional data on Atomichrons are listed in Fig. 21. It must be pointed out that the data in this figure are intended to give information on orders of magnitude only. More precise data on accuracy and stability would require a detailed description of the measuring method.

Efforts to increase further the precision in atomic-beam standards have been going in two directions, to a large extent under Signal Corps sponsorship: first, the "broken-beam experiment" to increase the transit time τ and with it $f/\Delta f = Q$[53] and secondly, studies of molecular spectra in the millimeter range[54,55] to be able to increase the numerator in the above fraction.

The emergence of practical cesium atomic beam frequency standards, with their inherently high accuracy, has stimulated several military applications requiring remotely located synchronized clocks with a precision of ± 1 microsecond or better. The problem of synchronizing clocks at great distances and maintaining this synchronization for extended periods of time prompted USASRDL to initiate Project WOSAC (World-Wide Synchronization of Atomic Clocks). This project, undertaken in cooperation with the U. S. Air Force, U. S. Navy, Harvard University, and the British Post Office, is expected to prove the practicability of synchronizing remote clocks by the clock transportation method, and maintaining the synchronization of these clocks by phase tracking VLF transmission signals controlled by a master clock. A recently completed phase of this experiment, using the clock transportation method, demonstrated that two clocks, located approximately 1000 miles apart, could be synchronised and maintained in phase to within 0.2 μsec for 32 hours.[56]

C. Ammonia Maser

Though cesium beam standards give the higher accuracy and are best suited for long-term and ground application, the maser looks promising, especially for missile-borne use, due to its high short-term stability, inherent ruggedness, and smaller size. It was first described by Gordon, Zeiger and Townes[42] and uses an electric dipole transition in ammonia, namely, the (3,3) inversion line, occurring at about 23,870 Mc. Fig. 25 illustrates the principle of the maser. A beam of NH_3 molecules passes through a state separator (focuser) which removes the molecules in the lower energy state from the beam. It is now comprised only of the higher energy-state molecules which enter a microwave cavity tuned to the transition frequency. There, the molecules make the transition to the unexcited state, emit radiation and sustain oscillations. Fig. 26 shows the internal design of a laboratory maser built at USASRDL, and Fig. 27 shows a small sealed-off maser for missile applications,

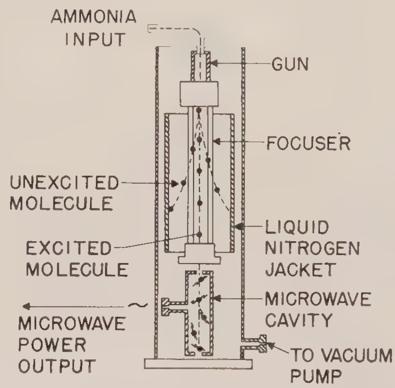

Fig. 25—Schematic of an ammonia maser.

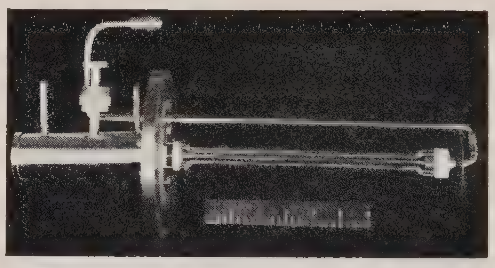

Fig. 26—Internal construction of an ammonia maser. Arrangement of parts as in schematic shown in Fig. 25.

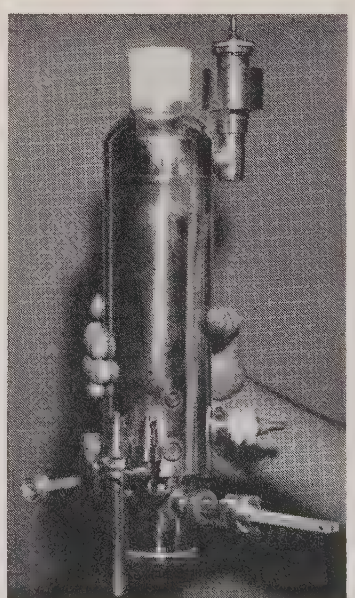

Fig. 27—Sealed-off maser for missile applications.

[52] J. Holloway, W. Mainberger, F. H. Reder, G. M. R. Winkler, L. Essen, and J. V. L. Parry, "Comparison and evaluation of cesium atomic beam frequency standards," Proc. IRE, vol. 47, pp. 1730–1736; October, 1959.

[53] D. Kleppner, N. F. Ramsey, and P. Fjelstadt, "Broken atomic beam resonance experiment," *Phys. Rev. Lett.*, vol. 1, pp. 232–233; October 1, 1958.

[54] V. W. Hughes, "Considerations on the design of a molecular-frequency standard based on the molecular-beam electric resonance method," *Rev. Sci. Instr.*, vol. 30, pp. 689–693; August, 1959.

[55] J. J. Gallagher, "Suitable molecules for utilizing millimeter-wave transitions for frequency control," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 604–617; May, 1959.

[56] F. H. Reder and G. M. R. Winkler, "World wide clock synchronization," IRE Trans. on Military Electronics, vol. MIL-4, pp. 366–376; April/July, 1960.

also developed at USASRDL.[57] It maintained its frequency to better than 5 parts in 10^{10} under a static acceleration of 30 G. The maser does not possess the high inherent accuracy of a cesium-beam standard, mainly because the resonance frequency of the cavity has a definite influence upon the maser output frequency. Much work has been accomplished, in USASRDL and elsewhere, to reduce this so-called cavity pulling effect, as well as the influences of other parameters on the output frequency. The following measures may yield accuracies and stabilities as shown in Fig. 21: symmetrical maser structure employing two beams[58] to reduce the Doppler effect, temperature-controlled cavity[58] or quartz cavity near a temperature for which the expansion coefficient goes through zero[59] to reduce frequency pulling by the cavity, usage of Zeeman modulation to tune the cavity to the center of the spectral line,[60] and reduction of residual pressure in the vacuum chamber.[61]

In order to reduce the K-band frequency of the maser to the desired value in the VHF range, miniaturized frequency translators have been developed at several places. Fig 28 shows the schematic of the double-loop equipment of USASRDL.[57] A klystron is phase-locked to the maser, and a harmonic of a quartz crystal oscillator is phase-locked to the klystron signal. Any instability of the 30-Mc reference oscillator cancels out. A one-loop translator was developed by the Diamond Ordnance Fuze Laboratories.[62] It is based on the coherent multiplication of the quartz controlled oscillator to a frequency in the K-band employing a varactor diode.

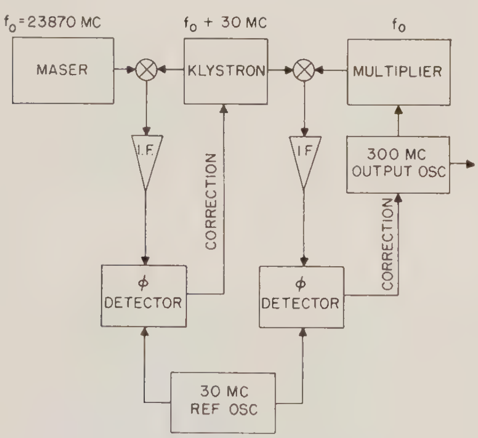

Fig. 28—Schematic of a double-loop frequency translator for the maser.

D. Gas-Cell Devices

In contrast to the cesium-beam standard and the maser, this type of atomic standard does not employ a beam, but uses the resonating gas enclosed in a small container. A considerable amount of work on gas cells has been accomplished in several places, some sponsored by USASRDL. Most effort has been concentrated on atomic rubidium or cesium undergoing the same type of transition as used in the cesium beam standard.[63–67] The reduction of the line width of the spectral lines is effected, as Dicke suggested, by having the gas atoms collide elastically with a neutral gas (buffer gas), such as argon, helium or neon. These collisions slow down the effective velocity of the atoms from the higher value of a straight thermal flight to the lower value of crisscross flight encountered in diffusion processes. The necessary change of the Boltzmann distribution for the hyperfine microwave transition under consideration is effected by the so-called method of optical pumping.[45] In optical pumping, the gas cell is illuminated with suitably polarized light of a wavelength corresponding to an optical transition of the atoms. The absorption and subsequent emission of this light can result in a rearrangement of the atoms within the group of hyperfine states belonging to the optical ground state, thus resulting in a much larger population difference between these hyperfine states responsible for the microwave transition. The intensity of the pumping radiation absorbed or scattered by the gas cell changes when the desired microwave transition occurs. This offers a very convenient way of detecting the microwave resonance with a high SNR.

Fig. 29 shows the schematic of a typical gas cell standard[64] using Cs^{133} and light absorption for the indication of resonance. A crystal oscillator is phase locked to the resonance frequency of the atomic transition. One serious disadvantage of a gas cell is the fact that the buffer gas produces a shift of the center frequency of the hyperfine transition, and this shift is a function of temperature and pressure; see Fig. 30.[64] Fortunately, different buffer gases produce frequency shifts in opposite directions, and mixtures of these gases can be found which

[57] F. H. Reder and C. J. Bickart, "A missile-borne maser frequency standard," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 546–565; 1959.

[58] R. C. Mockler, J. Barnes, R. Boehler, H. Salazar, and L. Fey, "The ammonia maser as an atomic frequency and time standard," IRE Trans. on Instrumentation, vol. I-7, pp. 201–206; December, 1958.

[59] F. O. Vonbun, "Maser laboratory frequency standard," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 618–628; May, 1959.

[60] F. O. Vonbun, "Proposed method for tuning a maser cavity," *Rev. Sci. Instr.*, vol. 29, pp. 792–793; September, 1958.

[61] L. D. White, "Ammonia maser work," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 596–602; May, 1959.

[62] W. K. Saunders, "A compact frequency translator for use with the ammonia maser," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 566–574; May, 1959.

[63] E. C. Beaty, P. L. Bender, and A. R. Chi, "Hyperfine transitions in rubidium-87 vapor," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 669–675; May, 1959.

[64] M. Arditi, "A gas-cell 'atomic clock' as a high-stability frequency standard," IRE Trans. on Military Electronics, vol. MIL-4, pp. 25–28; January, 1960.

[65] J. M. Andres, D. J. Farmer, and G. T. Inouye, "Design studies for a rubidium gas-cell frequency standard," IRE Trans. on Military Electronics, vol. MIL-3, pp. 178–183; October, 1959.

[66] R. M. Whitehorn, "Gas-cell frequency standards using buffer gases and buffer walls," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 648–659; May, 1959.

[67] C. Alley, "Triple-resonance method to achieve narrow and strong spectral lines," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 632–647; May, 1959.

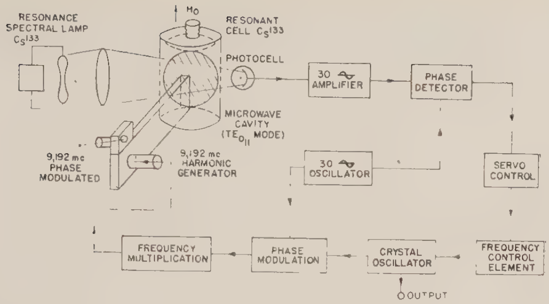

Fig. 29—Gas-cell atomic clock using optical pumping and optical detection. (Courtesy M. Arditi, ITT Laboratories.)

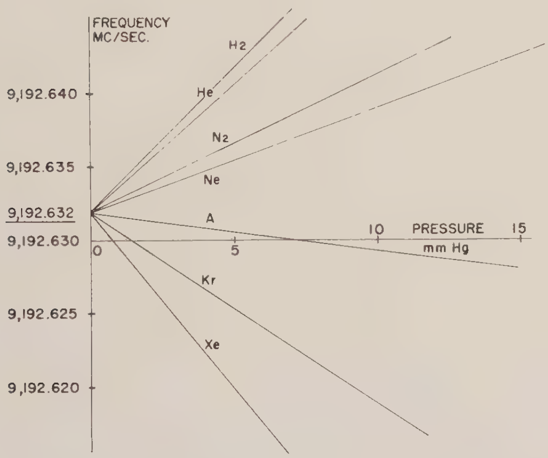

Fig. 30—Dependence of frequency of a gas-cell atomic standard on the gas pressure in the cell. (Courtesy M. Arditi, ITT Laboratories.)

produce only a very small shift within a large range of pressure or temperature variations. With the usage of optical detection, a mixture of 12 per cent neon and 88 per cent argon as a buffer gas, and a temperature stability of 0.1°C, data as indicated in Fig. 21 can be obtained.[68] Though a gas cell standard does not possess the inherent accuracy of a cesium beam standard, it can be built in a small size.

IV. Conclusions

Progress in the development of military frequency-control devices has yielded an improvement in accuracy or more than four orders of magnitude in twenty years. This progress in technology has been accompanied by widely-diversified applications for military purposes. Once primarily a component for communications only, this new generation of frequency control devices will now be used for missile and satellite tracking, precision radio location, navigation, and purely scientific experiments as well. The next decade may very well show the development of even more accurate devices based on yet unexplored phenomena, which, in turn, will stimulate wider military and scientific applications.

V. Acknowledgment

The authors desire to express their appreciation for stimulating discussions with members of the Frequency Control Division, USASRDL, especially with Drs. Bechmann, Guttwein and Reder, and Messrs. Bernstein Layden, Mulvihill, and Stanley.

The Signal Corps Synthetic Quartz Program*

J. M. STANLEY†

Summary—The role of the Signal Corps in developing the various techniques now being used to synthesize quartz crystals is reviewed from the standpoint of the quality of the material produced, growth rate, growth conditions, seed orientation, feed materials, cost, and suitability for production.

Differences in the structure of synthetic quartz are indicated by variations in the optical absorption coefficients of X-irradiated quartz plates taken from different growth directions. The optical absorption measurements on the different types of synthetic quartz are compared with one another.

Differences in the structure of natural and synthetic quartz are also indicated from measurements of Q made on 5-Mc high-precision resonators fabricated from samples of synthetic quartz grown under different conditions and from the occurrence of large absorption peaks at low temperatures (50°K) noted when measuring such resonators. Data is presented to show that synthetic quartz grown in the Z-direction possesses higher Q's than other quartz growth directions. None of the 5-Mc units made from synthetic quartz approach the high Q typical of natural quartz 5-Mc units between −60°C and 100°C.

Comparison of the frequency temperature characteristics of overtone high frequency resonators made from synthetic quartz with those made from natural quartz show them to be about the same. The growth direction and impurity content, however, change the optimum orientation angle and inflection temperature.

Resonators processed from synthetic quartz for operation in the 60–202-Mc range are shown to perform as satisfactorily as similar resonators made from natural quartz. No differences were noted in the processing characteristics, frequency temperature coefficients, and resonance resistances of the two materials. In both natural and synthetic quartz VHF resonators the Q is shown to decrease at about the same rate with increasing frequency.

The processing potentials and current material costs of natural and synthetic quartz are compared with each other. Areas where additional quartz synthesis information is needed are discussed briefly.

I. Introduction

During World War II the consumption of quartz for frequency control applications rose to 1,880,000 pounds per year. More than 29,000,000 crystal units were produced from this quantity of quartz in 1944. The many difficulties in getting sufficient supplies of radio-grade quartz from Brazil to maintain this production rate during this conflict provided the impetus for initiation of a program to synthesize this strategic material. It was realized then that only by this means could the United States become completely independent of foreign sources of radio-grade quartz. Deposits of radio-grade quartz in the United States are very scarce and not nearly sufficient to meet normal requirements for this material.

The first intensive effort to synthesize quartz crystals was started by the Signal Corps shortly after the war. The initial contracts sponsored by the Signal Corps for the synthesis of quartz used the approach developed by Professor Nacken[1] in Germany during the war. This technique used high pressure autoclaves to contain the pressures developed at the crystallization temperature by the weak basic solutions used as a solvent for the amorphous silica feed material. The solutions were heated to a temperature of about 400°C where the difference in solubility between the amorphous feed material and the crystalline quartz seed was expected to maintain the growth cycle. It turned out, however, that growth could not be maintained for longer than a two-day period. This was caused by devitrification of the feed material, which resulted in equilibrium being established between the feed, seed, and solution.

Effort was then concentrated on using the temperature difference approach initially investigated by Spezia[2] around the turn of the century. As in the case of Nacken's experimentation, weak basic solutions and high temperatures and pressures were needed for solution of the feed and growth of the seed. Unlike his work, however, both the feed and seed were crystalline quartz, and growth could be maintained as long as feed material was available. This was accomplished by holding the feed material at a higher temperature than the seed. This temperature difference caused the feed material to go into solution at the hot end, then to be carried by convection currents to the cooler zone where it became supersaturated and deposited silica (SiO_2) on the seed.

II. Quartz Growth Systems

A. Medium Temperature and Pressure Growth on Minor Rhomb Seeds

The Signal Corps contractors who investigated the Nacken method were Antioch College, Yellow Springs, Ohio, and Brush Laboratories, Cleveland, Ohio. The latter company, now known as the Clevite Research Center, turned their research efforts to Spezia's temperature gradient idea after unsuccessfully attempting to develop Nacken's method. Their initial studies[3] in small vertical autoclaves were confined to the system, $Na_2O—CO_2—SiO_2—H_2O$. The solutions were weakly basic, about 2 molar, and the temperature covered a range above and below the critical temperature of water. The degree of fill and temperature of the run determined

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

[1] R. Nacken, "Hydrothermal Mineral synthese als Grundlage für Zuchtung von Quartzkristallen," *Chem. Z.*, vol. 74, pp. 745–749; 1950.
[2] G. Spezia, "Sull'accrescimenta del quarzo," *Atti Accad. Sci. Torene*, vol. 44, pp. 95–107; 1908.
[3] D. R. Hale, "Hydrothermic synthesis of quartz crystals," *Ceramic Age*, vol. 56, pp. 22–24; November, 1950.

the pressure. The seeds were square blanks cut parallel to the minor rhomb surfaces of quartz. In some instances square AT blanks were used as seeds. Brazilian Lascas quartz was used as the feed material. The feed or nutrient material was placed in the lower portion of the autoclave and the seeds in the upper portion. Heat applied to the bottom of the autoclave provided the thermal convection needed to carry the dissolved feed material to the cooler seed area.

Sufficient information was obtained from this experimental set-up to indicate the feasibility of growing quartz crystals by the temperature difference method.

To improve the circulation and increase the growth rate of synthetic quartz, the Na_2CO_3 process was modified by mounting the autoclaves in a horizontal position and rocking them a prescribed number of degrees off the horizontal. The autoclave, shown in Fig. 1 consisted of two chambers, one for the feed material (Brazilian Lascas) and the other for the quartz seeds (CT blanks). The seed chamber was maintained at 355°C, and the feed chamber at 366°C. The seed plates used were free of electrical and optical twinning and other flaws. Average growth rates were about 0.5 mm/day normal to the minor rhomb surface. With these growth rates it was possible to produce in a 100-liter autoclave about 50 pounds of synthetic quartz from 220 seeds in a period of seventy-five days. The dimensions of the seeds were $1\frac{1}{4}\times 1\frac{3}{4}\times 0.05''$. Seeds of this size, under the conditions specified above, produced crystals weighing about 100 grams in a period of 75 days. This size was estimated to be about optimum for the processing of resonators.

A Signal Corps pilot plant set up by Clevite, consisting of four 100-liter autoclaves and two 20-liter autoclaves and operating under the experimentally determined conditions specified above, produced 1200 pounds of synthetic quartz in a year on seeds cut parallel to a quartz minor rhomb face. The crystals were examined in accordance with the synthetic quartz specification, and the big majority of those produced met quality and size requirements.

B. Y-Bar Growth in Rocking Two-Chamber Autoclaves

Because the length of time involved in producing synthetic quartz crystals from minor rhomb seeds made the cost of this material appreciably higher than natural quartz, it was decided to investigate the possibility of using other seeds with the Na_2CO_3 system. The most promising of these was the *Y*-bar seed developed by Clevite under Signal Corps contract. These seeds (Fig. 2) are generally $\frac{1}{8}$ inch square in cross section and about 7 inches long. Growth occurs on these seeds in the *Z* and *X* directions at three different rates. The most rapid rate is normal to the *Z* axis followed by growth in the $+X$ direction. The slowest growth occurs in the $-X$ direction. Fig. 3 shows the unusual form of the *Y*-bar crystal and the characteristic surfaces on the artificial *X* and *Z* faces. Growth in the *Z* direction produces a characteristic cobblestone surface which is accentuated by rapid growth rates and minimized by slow growth rates. It can be seen from Fig. 3 that the bar shape of the crystal makes it ideally suited for the production of oscillator plates.

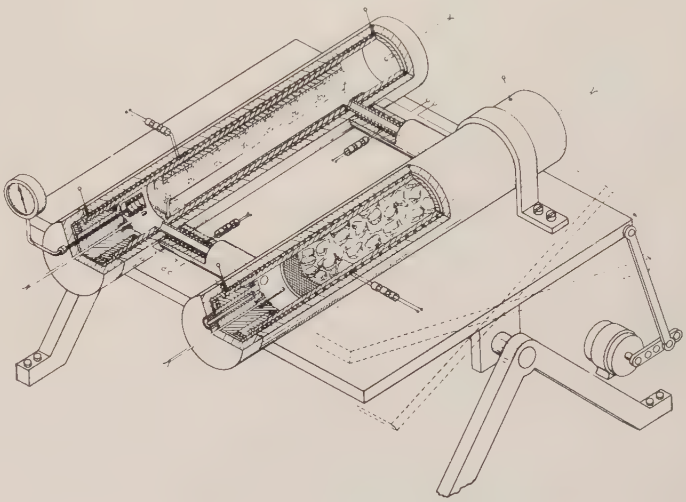

Fig. 1—Horizontal rocking two-chamber autoclave.

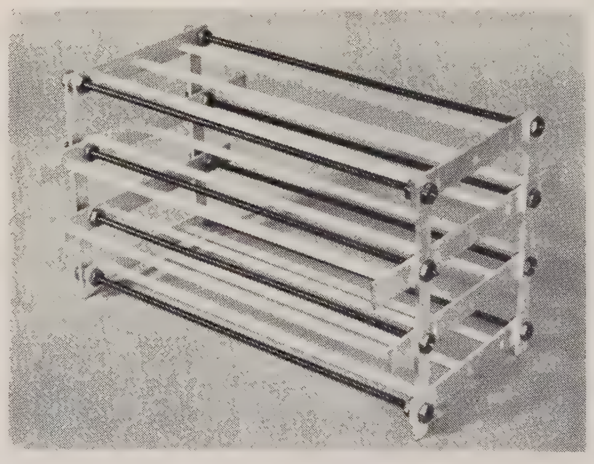

Fig. 2—Quartz *Y*-bar seeds.

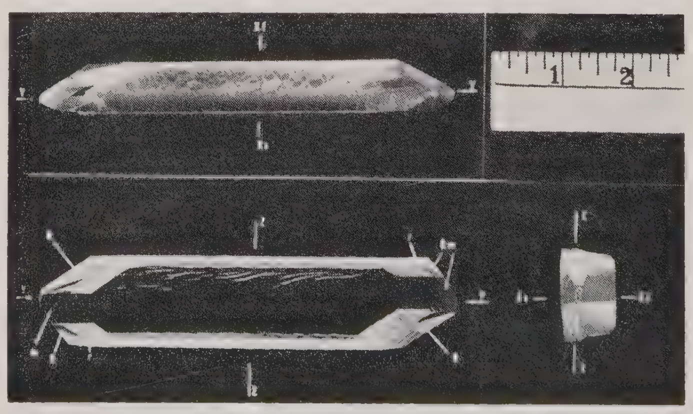

Fig. 3—Synthetic quartz *Y*-bar crystal.

Conditions established for the optimum growth of *Y*-bar crystals in rocking two-chamber autoclaves differed mainly from the conditions established for minor rhomb growth in the degree of fill (75 per cent), solution concentration (0.83 molar), and pressure (7000–8000 psi). Growth rates ranged from 0.4 to 0.9 mm/day in the *Z* direction and from 0.23 mm to 0.45 mm in the *X* direction. A substantial increase in production capability was obtained from the use of *Y*-bar seeds. In a year's time, a total of 7883 *Y*-bar crystals weighing 3575 pounds were produced in four 100- and two 20-liter autoclaves. The selling price of this material was $46.70 per pound.

C. *Y-Bar Growth in Vertical Single Chamber Autoclaves*

During the course of experimental work on the growth of *Y*-bar seeds in horizontal rocking autoclaves, information was experimentally obtained on the possibilities of growing *Y*-bar crystals in vertical single-chambered autoclaves. Economic comparison of the rocking two-chamber and vertical single-chamber stationary autoclaves showed up the many advantages of the latter. Using this as a basis, the Signal Corps sponsored a contract for the pilot plant growth of *Y*-bar seeds in this type of autoclave. The Signal Corps contractor on this investigation was Sawyer Research Products, Eastlake, Ohio.

For this work, six new 79-liter autoclaves were obtained. The inside diameter of these autoclaves was 8 inches and the design pressure and temperature 10,000 psi and 450°C. As shown in Fig. 4, the cylindrical cavity inside these autoclaves is divided into two chambers by a baffle located at its middle height. The growth mechanism is provided by the temperature difference between the areas above and below the baffle. Brazilian Lascas quartz feed material is located in the lower portion of the autoclaves below the baffle, and the *Y*-bar seeds in the upper portion above the baffle. Except for the degree of fill (80 per cent), growth conditions were about the same as those used with two-chambered autoclaves. The yield per autoclave was approximately 88 pounds. Defective growth caused by excessive solid inclusions, cracks due to oversized growth, undersized growth, spontaneous nucleation, and blue haze were virtually eliminated by reducing the growth rate. This also helped to reduce, but not to eliminate, crevice flawing.

The six autoclaves used in this pilot plant study produced 7365 *Y*-bar crystals weighing 3222 pounds in one year.

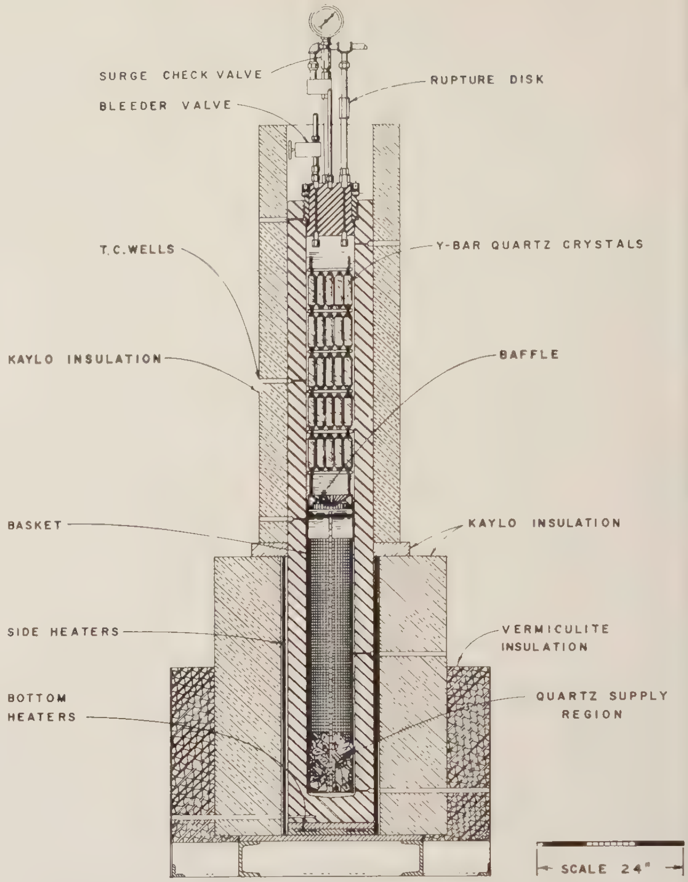

Fig. 4—Vertical autoclave for growth of quartz at medium temperatures and pressures.

D. *Quartz Growth From Domestic Source Materials*

The Signal Corps is currently sponsoring further pilot plant work at Sawyer Research Products to modify the growth process so that domestic source material can be used in place of Brazilian Lascas quartz. Continued use of the latter material would, of course, defeat the original purpose of the synthetic quartz program, to make the United States independent of a foreign source of supply of this strategic material.

A little work had been done previously by Clevite on this problem with fairly promising results. The domestic materials used as nutrients in this earlier work were quartzite gravels from North Carolina and Ohio. Both materials were 99.2 per cent pure. The *Y*-bars produced from them were grown under standard conditions in two-chamber rocking autoclaves. They tended to have a somewhat larger quantity of solid inclusions, optically twinned spots and cracks than the average *Y*-bar grown from Brazilian Lascas. A slight change in the habit (form) of these *Y*-bar crystals was noted also. This was believed due to a change in the crystal growth pattern caused by an impurity contributed by the quartzite. A similar disturbance in growth habit was noted in the *Y*-bars being grown from domestic quartzites from another section of North Carolina and from Massachusetts. The latter crystals were grown by Sawyer Research Products under their current Signal Corps contract. The effects of this modification on resonator characteristics is still to be determined.

Efforts are currently being made under the referenced contract to eliminate this habit modification and to

grow radio-grade quartz on Z-cut plates from sodium carbonate solutions. Information obtained previously on the improved quality of Z direction growth over other growth directions was the basis for initiating this work. Bars obtained from such seeds retain the desirable form factor of the Y-bar without the disadvantage of including the poorer quality X-growth material. It is anticipated that eventually the Z-bar will replace the Y-bar in the production growth of synthetic quartz crystals.

At the present time Sawyer is selling Y-bar crystals for \$27.50 per pound for quantities in excess of 500 pounds. The quoted price for smaller quantities is \$35.00 per pound. The price of natural quartz of comparable size and with a high useability is about \$6.00 per pound. This seems to be a big difference in favor of natural quartz, but the labor savings and increased blank yield of the synthetic material makes its cost comparable to that of natural quartz.

E. Quartz Growth at High Temperatures and Pressures

One of the areas investigated by Brush Laboratories during the early days of their efforts to synthesize quartz was the region above the critical temperature of water. Because of their success with the sodium carbonate system below the critical, Brush chose this system for the quartz synthesis work above the critical. Considerable difficulty was experienced in these experiments because of the occurrence of spontaneous crystallization. This fact coupled with the pressure limitations imposed by the state of Ohio for vessels of the type used prompted the decision to confine further experiments to temperatures below the critical.

In the meantime, the Signal Corps sponsored a contract with Western Electric to investigate the possibilities of growing synthetic quartz above the critical. It was felt at the time that the growth rate would be speeded up appreciably at higher temperatures because of the large change in density with temperature in this region. Like the Brush approach, the initial efforts to grow synthetic quartz above the critical were made in Na_2CO_3 solutions. Relatively high growth rates were obtained, but again like the previous Brush work, trouble was experienced with spurious seed formation. Because of that, a shift was made to the system $Na_2O—H_2O—SiO_2$. Previous work by Nacken[1] in an isothermal system showed that quartz would dissolve but not recrystallize in NaOH. The equipment and method used was much like the Na_2CO_3 process, in that a temperature difference between the feed and seed zone maintained the continuity of growth. Brazilian Lascas quartz feed material and minor rhomb seeds were placed in the lower and upper portions of a vertical autoclave respectively. A 10 per cent baffle was used to improve the circulation of the 0.5N NaOH solution. The baffle was positioned, as shown in Fig. 5, between the source material (nutrient) and seeds. Temperatures at the feed (source)

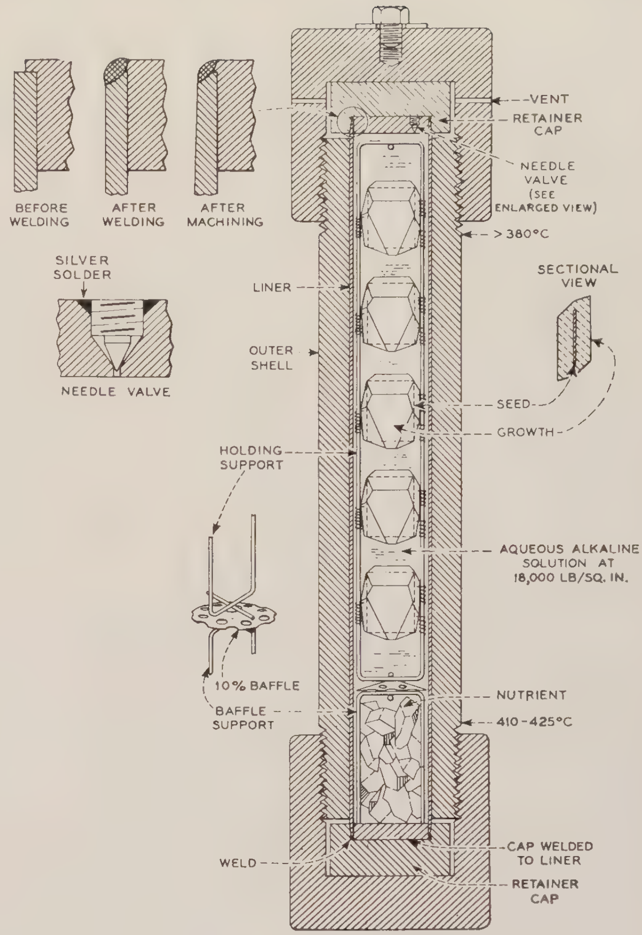

Fig. 5—Vertical autoclave for growth of quartz at high temperatures and pressures.

area ranged from 410°C–425°C, and in the seed area they were about 380°C. The degree of fill and estimated pressure were 80 per cent and 20,000 psi, respectively. A steel tube (liner) sealed by welding was used to enclose the seeds, feed, solution, and baffle.

Because the temperature, degree of fill, and temperature difference were higher than the Na_2CO_3 system, it was possible to achieve rates averaging about 1.27 mm/day in a direction normal to the minor rhomb. Growth rates as high as 2.5 mm/day were obtained on Z-cut seeds under the same conditions.

An independent study made by Laudise[4] of Bell Telephone Laboratories of the factors influencing the rates of growth of synthetic quartz in the NaOH system demonstrated that growth rates as high as 5 mm/day could be achieved on Z-cut seeds at a crystallizing temperature of 385°C by increasing the degree of fill to 86 per cent. This was accomplished without affecting quality. However, at the same temperatures, with lower degrees of fill, the growth on Z-cuts was slower and

[4] R. Laudise, "Factors influencing the rate of growth of synthetic quartz crystals," *Proc. 13th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 17–36; May, 1959.

flawed. It is apparent from growth rate considerations alone that the NaOH system is very promising. However, because of the very high pressures (20,000 psi) generated in this system, it was extremely difficult to prevent leaks from occurring in the autoclaves.

The high temperature NaOH process[5] developed by Dr. A. C. Walker of Western Electric under Signal Corps contract was later carried to the pilot plant stage by this organization some time after the Signal Corps contract was completed. The process to be used in the pilot plant is, with some modifications, basically the same as the original process. Exact information concerning it is not available. It is understood, however, that the temperature is somewhat lower and the degree of fill somewhat higher than the original process developed under Signal Corps contract. A more dependable seal is being obtained with a new design of autoclave, and Z-cut seeds are being used exclusively.

Since the pilot plant will only be used to produce quartz for Western Electric needs, information on per pound cost and production capability are not available at the present time. However, it can be assumed from the growth rate capabilities of the system that the cost per pound will be at least as low as that quoted for synthetic quartz produced by the Na_2CO_3 process.

F. Low Temperature and Pressure Quartz Growth

During the development of the process for growing Y-bars in Na_2CO_3 solutions, an investigation was conducted by Clevite under Signal Corps contract into the possibilities of preparing synthetic quartz crystals at lower temperatures and pressures. The objective was to determine whether an appreciable reduction in cost would result from a low-pressure system featuring simplicity and economy of design.

The first experiments were conducted in 0.74 cubic feet rocking autoclaves at 300°C and 1200 psi. While the quality of growth was high, the rate was about $\frac{1}{5}$ normal (0.1 to 0.15 mm/day perpendicular to the minor rhomb face). Additional low-pressure growth studies conducted in welded pipe vertical autoclaves at crystallization temperatures ranging from 270°C to 285°C and pressures from 1100 to 1200 psi produced growth rates ranging from 0.05 mm to 0.12 mm/day. In subsequent experiments, the rate was increased to 0.250 mm/day. This, however, was the maximum that could be achieved at that time. Although it was realized at the time the low-pressure work was started that the rate would probably be somewhat slower than standard, it was expected to be compensated for by savings in instrumentation. Early work in this region, however, did not bear this out.

More recent work being conducted in the U. S. Army Signal Research and Development Laboratories (USASRDL) in the low pressure (1100 psi) and temperature (280°C) region is showing the feasibility of producing synthetic quartz crystals on Z-cut seeds at rates comparable to that achieved by the medium temperature and pressure process (0.5 mm/day). The increase in the growth rate at low pressures is being accomplished by the addition of mineralizing agents. While the visual quality of these crystals is good, the effect of the additions on the other properties of quartz has not been determined as yet.

G. Advantages of the Various Quartz Growth Systems

The chief advantage of synthesizing quartz crystals by the Na_2CO_3 process is the relatively low temperatures and pressures required to produce acceptable material at growth rates which will make the cost competitive with natural quartz. To increase the growth rate in this system, Sawyer has been conducting its runs at higher pressures by increasing the degree of fill. They are limited, however, to a pressure of about 12,000 psi. Above that pressure, the growth has tended to be flawed. Another advantage of the sodium carbonate process over the NaOH high pressure process is reduced equipment costs. This advantage, of course, stems from the fact that Na_2CO_3 process develops much less pressure than the NaOH process because of a lower crystallization temperature. The NaOH process, because of its higher crystallization temperature, degree of fill, and temperature difference, has a much more rapid growth rate. To produce crystals of sufficient size for the fabrication of oscillators requires a period of about thirty days in NaOH, while the Na_2CO_3 process requires about forty days to produce Y-bars for this purpose. Since information is not available on the costs involved in producing synthetic quartz by the high-temperature process, no direct comparison can be made with available cost figures for the medium temperature (Na_2CO_3) process. The chief disadvantage of the high temperature NaOH system is the increased costs of the autoclaves needed for this work. Because of the higher pressures required there is also a greater tendency for leaks to develop in the NaOH process. However, much higher temperature differences between the feed and seed areas can be tolerated in the latter process without the occurrence of spontaneous nucleation.

From a visual and applications standpoint there is not much difference between the quality of the crystals produced by either of the two processes developed under Signal Corps contract. The crystals from both processes are free of twinning, solid and liquid inclusions and are suitable for the big majority of military and commercial applications. Only in the area of high precision crystals is there room for improvement.

III. Characteristics of Natural and Synthetic Quartz

A. Frequency Temperature Characteristics

While the synthetic quartz being produced by the techniques described here are suitable for most applications, there are certain structural variations in these materials which are not present in natural quartz. This was

[5] A. C. Walker, "Growing quartz crystals for military needs," *Electronics*, vol. 24, pp. 96–99; April, 1951.

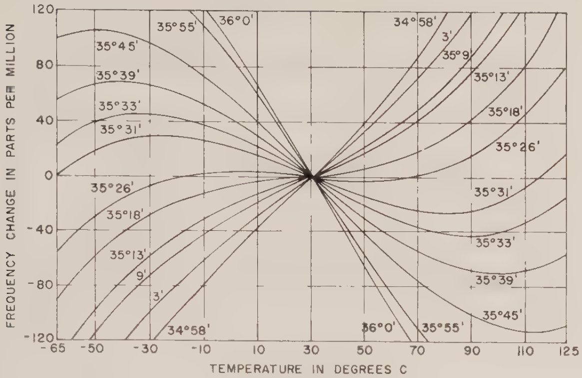

Fig. 6—Frequency temperature characteristics of natural quartz 29-Mc (fifth overtone) AT-cut resonators.

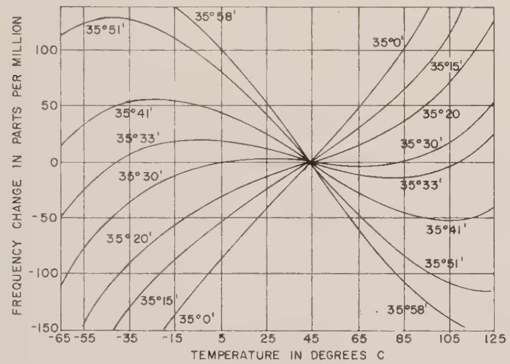

Fig. 7—Frequency temperature characteristics of minor rhomb synthetic quartz 29-Mc (fifth overtone) AT-cut resonators.

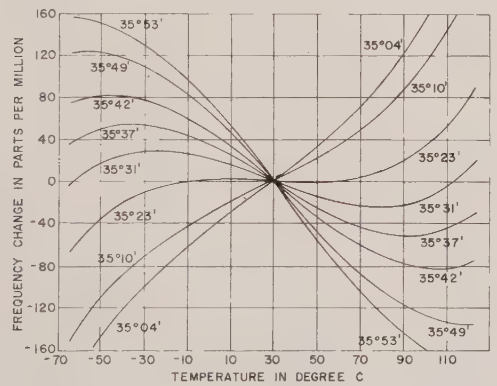

Fig. 8—Frequency temperature characteristics of Y-bar synthetic quartz 29-Mc (fifth overtone) AT-cut resonators.

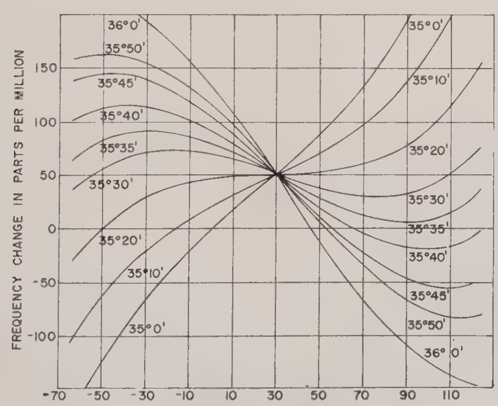

Fig. 9—Frequency temperature characteristics of Z-growth synthetic quartz 29-Mc (fifth overtone) AT-cut resonators.

first noted in resonators which were prepared from crystals grown on minor rhomb seeds. The optimum orientation angle, minimum frequency change over the temperature range −55° to +90°C, was found by Bechmann[6] to be about six minutes higher in synthetic resonators prepared from minor rhomb growth than the same resonators prepared from natural quartz. Chi's[7] frequency temperature curves of fifth-overtone 29-Mc resonators prepared from natural quartz and minor rhomb synthetic quartz, shown in Figs. 6 and 7, illustrate this difference. The use of Y-bar or Z-cut seeds, however, produces synthetic quartz with the same frequency temperature characteristics as natural quartz. Figs. 8 and 9 illustrate the frequency temperature characteristics of fifth-overtone 29-Mc units prepared from these two types of synthetic quartz. The latter curves were also prepared by Chi. King[8] noted similar differences between the various growth directions of synthetic quartz and natural quartz.

Differences in the inflection point, the temperature at which the curvature changes from negative to positive, of resonators prepared from minor rhomb synthetic quartz, and natural quartz were also noted by Chi.[7] He found that the minor rhomb material had an inflection temperature of 43°C. Natural quartz has an inflection temperature of 30°C.

Other differences between various growth directions in synthetic quartz were observed by Hammond[9] when irradiating Y-bar quartz with two million volt gamma rays. His experiments showed that the X-direction growth of the Y-bar quartz became appreciably darker than the Z-direction, indicating a greater concentration of impurities in this direction. Confirmation of this assumption was obtained by spectrographic analysis.

Variations in the impurity content of various growth directions of synthetic quartz are indicated in Table I.

TABLE I
(Atoms per 10^6 Si Atoms)

Impurity Element	Minor-r	+X	−X	Z
Al	151	60	93	47
Na	167	39	94	105
Li	1.0	4.3	13	ND*
Fe	39	76	49	51
Mg	10	11	19	16
Ca	7.3	14	19	18
Cu	ND*	0.75	1.4	9.5

* Not detected.

[6] R. Bechmann, "The frequency temperature behaviors of natural and synthetic quartz," Proc. IRE, vol. 43, p. 362; March, 1955.

[7] A. R. Chi, "Some resonator properties of synthetic and doped synthetic quartz," 1956 IRE Convention Record, pt. 9, pp. 70–75.

[8] J. C. King, "The anelasticity of natural and synthetic quartz at low temperatures," *Proc. 11th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 62–77; May, 1957.

[9] A. R. Chi, D. L. Hammond, and E. A. Gerber, "Effects of impurities on the resonator properties of quartz," Proc. IRE, vol. 43, p. 1137; September, 1955.

B. Optical Absorption of Natural and Synthetic Quartz

Studies[10] conducted by Augustine of the Clevite Research Center under Signal Corps contract to determine the optical absorption coefficients of synthetic quartz taken from different growth directions also demonstrated differences in the various types of synthetic quartz. Data obtained in these studies on the absorption spectra of *Z*, plus *X*, minus *X*, and minor-*r* growth quartz produced in ordinary growing solutions are shown in Fig. 10. The plates used in this study were cut and polished in pairs. One plate was irradiated to "saturation" with tungsten K-alpha radiation from a General Electric XRD-3 X-ray source using 50 kv and 50 ma. Transmission measurements were made on a Bechmann Model DU Quartz Spectrophotometer.

As can be seen from Fig. 10, *Z*-growth synthetic quartz shows very little evidence of absorption peaks and extremely low absorption. Plus *X* and minor-*r* growth quartz shows, on the other hand, much higher absorption and definite indication of peaks in the 220–230 mu, 450–460 mu and 625–650 mu regions. The higher absorption coefficients of the minor-*r* and plus *X* directions is due to a greater concentration of aluminum impurity believed to come from the Brazilian Lascas quartz used as source material in the growth experiment.

C. Precision Resonators from Synthetic Quartz

The limitations of synthetic quartz for precision applications were noted in studies conducted by King[7] of Bell Telephone Laboratories under Signal Corps contract. The various types of synthetic quartz evaluated in his study included among others quartz grown on minor rhomb seeds at high temperatures and pressures in sodium hydroxide solutions (Bell Telephone Laboratories) and at medium temperatures and pressures from sodium carbonate solutions (Clevite Research Center) and *Y*-bar quartz (Clevite Research Center). Resonators processed from this quartz were of the 35 AA type developed by Bell for the Air Force for use as frequency standards. These crystal units were designed for operation at 5 Mc on the fifth overtone.

The series resonance resistance of these units and similar natural quartz units over the temperature range −65°C to 100°C showed interesting differences between the synthetics, and between the synthetics and natural quartz. In the neighborhood of 70°C at 5 Mc, all the synthetic materials show well-defined resistance peaks, whereas natural quartz does not. At the low end of the temperature range, all the synthetic groups show a greater proportionate increase in resistivity than does natural quartz. Only in the region of 0°C does one of the minor rhomb synthetics approach the resistance of natural quartz. At the lower temperatures the resistance curves suggest the existence of either a much broader dislocation reaction than that observed in natural quartz, a peak of greater magnitude, or a relaxation absorption characterized by a different activation energy.

When resistance measurements were made by King on natural and synthetic quartz (*Y*-bar) 5-Mc resonators over the range from 100°K to 1.2°K certain additional characteristics became apparent. These are shown in Fig. 11. In the liquid helium range the resistance curve for natural quartz continues to drop, although there is a definite indication of two absorption peaks, one at 50°K and one at 20°K. The resistance of the two *Y*-bar resonators is similar to that for natural quartz in that the same two peaks occur at the same temperature. However, the relaxation absorption is very much larger (>3000 ohms) in the synthetic units. In natural quartz, this stress-induced relaxation absorption is attributed to the presence of impurities.

On the basis of the information collected by King, it is doubtful that synthetic quartz could be used for precision resonator applications without some modifica-

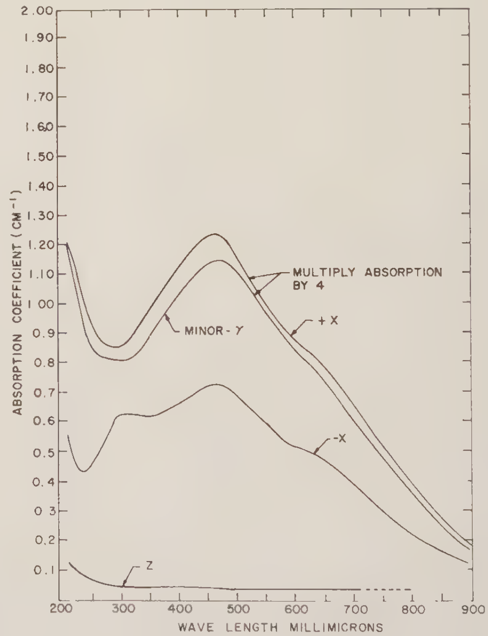

Fig. 10—Absorption spectra of various synthetic quartz growth directions.

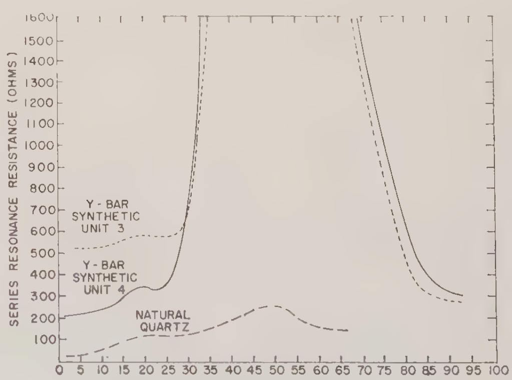

Fig. 11—Anelasticity of 5-Mc natural and synthetic quartz resonators at low temperatures.

[10] F. Augustine, "Improving the quality of synthetic quartz," *Proc. 12th Annual Symp. on Frequency Control*, Asbury Park, N. J., pp. 68–83; May, 1958.

tion. Some success has been achieved by him toward that end by heating the quartz in a dc field to a temperature slightly less than the alpha to beta inversion (573°C). Treatment of synthetic quartz in this manner has decreased the lattice spacing, and eliminated the 50°K absorption peak. Heat treatment alone has been found to be beneficial in reducing, but not in eliminating, the 50°K absorption peak. As yet, it has not been possible to reduce or eliminate this peak by modification of the growth process.

IV. Modification of Synthetic Quartz

The increase in the degree of precision with which resonators are fabricated has made it possible to distinguish between the effects of imperfections in quartz and variations in the fabrication of the resonator. In addition, the quartz synthesis technique provided a likely means of introducing controlled amounts of impurities into the quartz lattice. This possibility of incorporating appreciable amounts of impurities into the quartz lattice during the growth cycle, and the likelihood of identifying the effect of each impurity, extended an enticing possibility of a custom-made material with a specific characteristic that is superior to that of natural quartz.

The Frequency Control Division, USASRDL, conducted an investigation to determine the effects of impurities upon the properties of quartz. The first phase[11] of this investigation was concerned with synthesizing quartz with added impurities.

Standard conditions established for the growth of quartz from Na_2CO_3 solutions were used to incorporate the impurities. The crystallization temperature was 350°C, the pressure 5000 to 6000 psi, the degree of fill 70 per cent, temperature gradient 20°C, and the strength of the solution 0.5 normal. Selection of materials for addition to the growth solutions was made primarily on the basis of valence and ionic radius of the impurity elements. All the elements in the periodic table that might fit on this basis were tried, but only aluminum in Group III and germanium in Group IV could be incorporated to an appreciable extent. Analysis of quartz grown on seeds of various orientations in the presence of added aluminum in one case and germanium in the other is summarized in Table II.

Although appreciable amounts of germanium could be incorporated during growth, the effect of this impurity on the frequency temperature characteristics of AT resonators is small. King showed, however, that a 5-Mc resonator prepared from a quartz crystal grown on a minor rhomb seed and containing both aluminum and germanium in concentrations of 0.01 and 0.01 to 0.03 per cent, respectively, had a rather striking increase of resistance with decreasing temperature beginning at approximately 0°C. There was also a relatively high resistance throughout the entire range of −60°C to +100°C.

The frequency temperature characteristics of aluminum doped resonators are, however, appreciably different from similar undoped resonators. This can be seen from Chi's[6] curves (see Figs. 12 and 13) of the frequency temperature characteristics of fifth-overtone 29-Mc resonators containing 100 and 50 PPM respectively of aluminum. Comparing these curves with the frequency temperature curves for natural quartz, Fig. 6, it can be seen that in the case of the 100 PPM aluminum

TABLE II

Impurity	Ionic Radius (Å)	Impurity Concentration in Solution (Normality)	Impurity Concentration in Crystal (PPM)	Seed
Ge^{+4}	0.53	0.5	3000	AT
Ge^{+4}	0.53	0.2	1000	AT
Ge^{+4}	0.53	0.25	3000	AT
Al^{+3}	0.51	0.015	200	AT
Al^{+3}	0.51	0.03	50	AT
Al^{+3}	0.51	0.015	100	Z

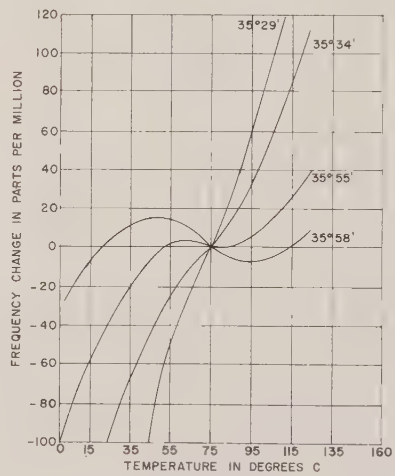

Fig. 12—Frequency temperature characteristics of 29-Mc aluminum doped (100 PPM) synthetic quartz resonators.

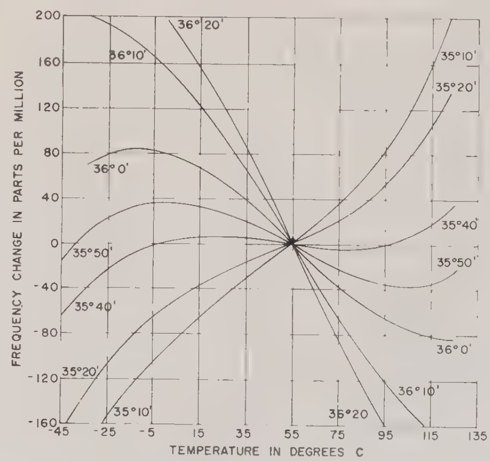

Fig. 13—Frequency temperature characteristics of 29-Mc aluminum doped (50 PPM) synthetic quartz resonators.

[11] J. M. Stanley and S. Theokritoff, "Incorporation of impurities in synthetic quartz crystals," *Am. Mineral.*, vol. 41, pp. 527–529; May-June, 1956.

doped resonator, the optimum orientation angle is shifted from 35°31′ to 35°58′. Information obtained from the derivative curves indicate a shift in inflection temperature of 40°C from that of natural quartz (30°C). The frequency temperature curves of the 29-Mc resonators containing 50 PPM of aluminum show departures from the characteristics of natural quartz approximately half those indicated by 100 PPM aluminum doped resonators. The optimum orientation angle of the 50 PPM doped resonators is 35°50′ and the inflection temperature is 55°C.

V. Synthetic Quartz VHF Resonators

Because some question existed concerning the suitability of synthetic quartz for VHF resonator applications study was made by Union Thermoelectric under Signal Corps contract of fifth-overtone resonators prepared from *Y*-bar synthetic quartz. The frequencies of the units studied were 60.75, 75, 83.54, 90, and 100 Mc.

Comparison of the series resonance resistance of the synthetic units at room temperature with similar units made of natural quartz showed no appreciable difference between the two.

Comparison was also made in this investigation of the series resonance resistance of fifth-overtone 83-Mc crystal units made from *Y*-bar synthetic quartz and natural quartz over the temperature range −55°C to 120°C. The units included in this study were all low in resistance to begin with. As can be seen in Fig. 14, the natural quartz units fluctuate slightly less in resistance than the synthetic units over the temperature range, but this is not considered significant.

Comparison was also made by Union Thermoelectric of the series resonance resistance of 12-Mc fundamental natural and *Y*-bar resonators over the temperature range −55°C to +90°C. As shown in Fig. 15, the differences between the two are not significant. Similar results were obtained on 16-Mc fundamental resonators prepared from natural quartz and synthetic quartz grown on *Y*-bar, minor rhomb, and *Z*-cut seeds. These units were made for operation on overtones and not on the fundamental.

In the processing of these natural and synthetic resonators, no difference was noted in the rate of stock removal, shape produced by the lapping process, or the surface finish from the same polishing process.

Evaluation of VHF resonators made from natural and synthetic quartz (minor rhomb seeds) was also conducted in the Frequency Control Division (FCD). This evaluation differed from the Union Thermoelectric investigation mainly in the crystal frequency, instrumentation, and temperature range over which the crystal was measured. The instrumentation used to make the measurements was devised by Hafner[12] of FCD. Basically, it is a bridge measuring system with a servo loop automatically controlling the generator frequency. Two of Hafner's curves, Figs. 16 and 17, show the variation in Q with decreasing temperature of natural and synthetic quartz resonators operated at 55 Mc (3rd overtone) and 202 Mc (11th overtone). It is apparent from these curves that there is not much difference between the Q of natural and minor rhomb synthetic quartz down to −100°C at either 55 or 202 Mc. At −100°C, however, the Q of the synthetic starts to decrease rapidly, while that of the natural shows little change. This decrease in Q of the synthetic, while occurring at a somewhat higher temperature than the 50°K absorption peak associated with 5-Mc high precision resonators, is believed to be due to the same defect. However, this defect should not affect operation of 202-Mc 11th-overtone resonators over the A temperature range (−55°C

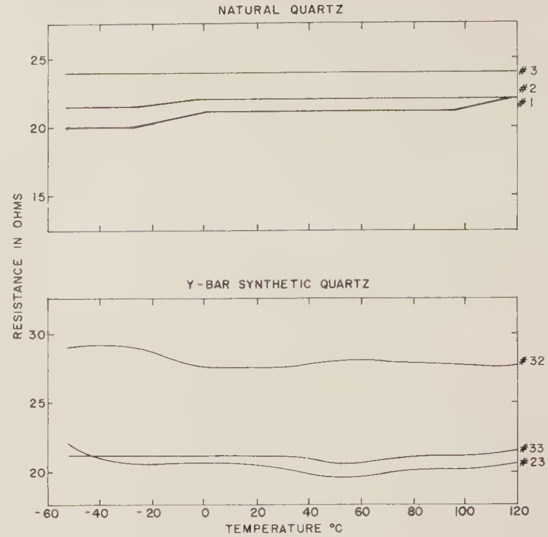

Fig. 14—Variation of resistance with temperature in natural and synthetic quartz 85-Mc fifth-overtone resonators.

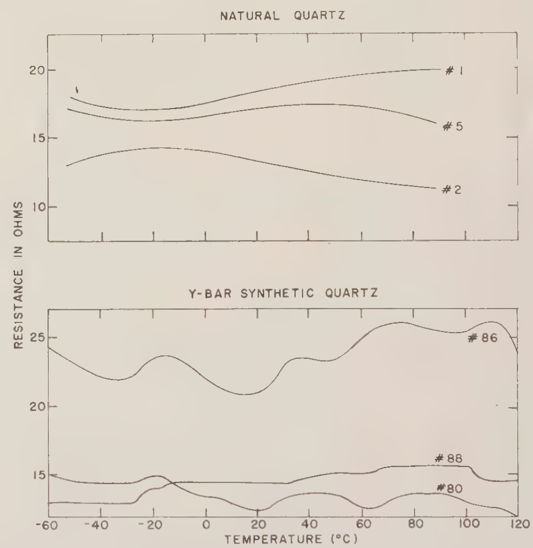

Fig. 15—Variation of resistance with temperature in natural and synthetic quartz 12-Mc fundamental resonators.

[12] E. Hafner, "A new method to simplify bridge type measurements on quartz crystal units," 1958 IRE National Convention Record, pt. 5, pp. 234–250.

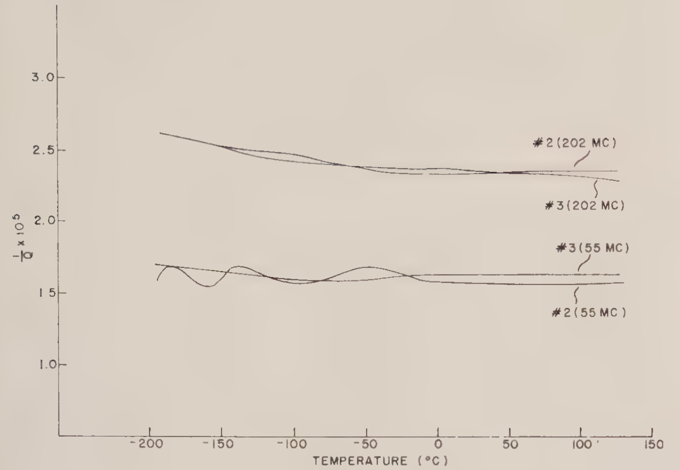

Fig. 16—Change in Q with decreasing temperature of third-overtone 55-Mc and eleventh-overtone 202-Mc natural quartz resonators.

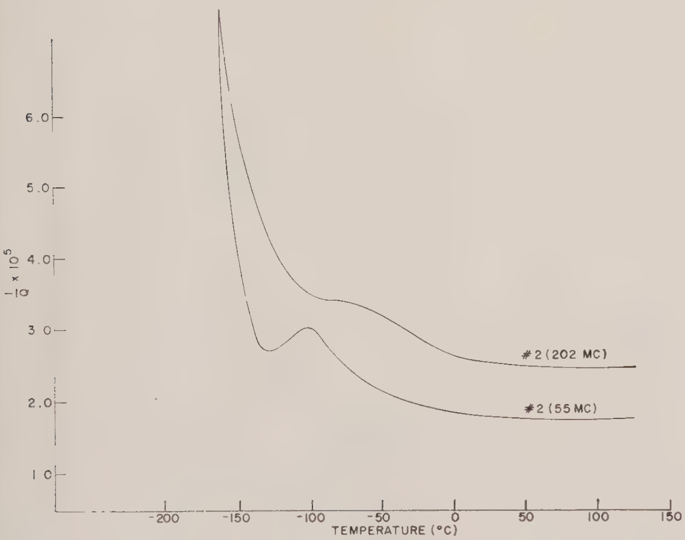

Fig. 17—Change in Q with decreasing temperature of third-overtone 55-Mc and eleventh-overtone 202-Mc synthetic quartz resonators.

to +90°C). Room temperature Q measurements made on 18.2-Mc fundamental crystals at overtones up to the 21st showed little difference between natural and Y and Z bar synthetic quartz.

On the basis of the data of Hafner and Union Thermoelectric, it can be safely said that synthetic quartz could be used in place of natural quartz at frequencies up to 202 Mc without any degradation of performance.

VI. Plans for Further Quartz Synthesis Investigations

While there are differences between natural and synthetic quartz as indicated here, they only affect the operating characteristics of precision resonators made from the synthetic material. For all other applications of resonators, the synthetic material performs as satisfactorily as natural quartz. Current production of precision resonators constitutes a very small fraction of the total number of resonators being manufactured at the present time, but because of expected increase in the use of single-sideband communication and crystals for satellite applications, a considerable expansion in the number of crystals needed to fill precision requirements is anticipated. Efforts in the future will therefore be directed toward improving synthetic quartz for precision applications by modification of growth conditions, use of purified growth systems, investigation of other systems, use of additives, and slow growth rates in preferred directions. These variables will be tried singly and in combination. Precision resonators fabricated from synthetic quartz growth by such variations will be used to determine the effect of same.

Another area where further quartz synthesis effort is needed is in the development of techniques to reduce the costs of producing Y-bars. While it has been indicated that the cost of the Y-bars compares favorably with that of natural quartz because of the much greater blank yield of the former, the difference is still not sufficiently large to encourage its extensive use by crystal manufacturers. Progress is being made in that direction by commercial organizations currently engaged in producing synthetic quartz, but there is still considerable room for improvement. Low-pressure and low-temperature growth currently being investigated in USASRDL has promising possibilities in this respect. Another possible way is to increase substantially the growth rates now being obtained by the medium temperature and pressure Na_2CO_3 process. A third way is to switch to the high temperature and pressure NaOH process.

It can be expected that further research effort in these two areas will produce a synthetic quartz with operating characteristics that are equal to or superior to those of natural quartz for all applications and which will cost much less than the natural material.

The Signal Corps Program on Magnetic Ferrites*

E. BOTH†, I. BADY†, SENIOR MEMBER, IRE, AND W. W. MALINOFSKY†

Summary—The ferrite research and development program pursued by the Signal Corps over the past twelve years is reviewed and its most significant results are described. The discussion includes all major phases and sub-tasks under this program; such as the work on low-loss high-permeability materials for communication uses at frequencies from 0.1 to 500 Mc, square hysteresis loop ferrites for computer applications, work on permanent magnet materials, and materials for microwave applications up to 100 kMc. In addition, studies dealing with the effect of impurities, preparation techniques, grain size and other parameters on certain material characteristics are mentioned briefly. A list of publications originating from this work is included.

THIRTEEN years ago, Snoek[1] reported on his extensive studies of complex ferric oxide compounds, conducted during the years of World War II at the Laboratories of the Philips Company in Holland. He showed that ferrite materials could be designed so as to yield a uniquely useful combination of characteristics: high permeability, low magnetic losses, and extremely low electrical conductivity. For magnetic high frequency devices, this development promised smaller size and weight, and possibly higher operating frequencies, than had been attainable with powder core materials—advantages of obvious importance to the Signal Corps.

Today, it can be stated that ferrites have far surpassed any expectations which could reasonably have been held for them at the time of their introduction. This new class of materials has grown at an unusually vigorous rate, not only with respect to the number and variety of materials and types available, but also with respect to the range of characteristics achieved in their development over the years. The original cubic spinel type compounds have been diversified to the point where they offer very respectable permeability and loss values for any frequency from audio to 500 Mc; in addition, they have acquired square loop characteristics for use in high speed computers, and they have been designed for a number of different microwave applications in which they play a unique and indispensable role. Furthermore, however, two new and equally important groups of ferrite compounds have joined the cubic spinel: the hexagonal ferrites, having either the magnetoplumbite structure or one of several intermediate magnetoplumbite-spinel structures, and the cubic garnet type ferrites. The former are mostly noted for their extremely high crystal anisotropy values, which have yielded excellent permanent magnet characteristics and also permit very interesting applications up to the millimeter wave region; the latter are highly useful for certain microwave applications where extremely narrow line-width is required.

Obviously, the enormous growth of this field suggested by the above thumbnail sketch has not come about by mere chance. It has taken the work of a great many people and the intricate processes of the interplay of their ideas to create the present state of the art. The Signal Corps was among the first to stimulate this effort, and it has participated in it continuously ever since. A brief account of these activities is believed to be in keeping with the purpose of the present special issue of these TRANSACTIONS.

It would be impossible to trace here all the work on ferrites which has been carried out under full or partial sponsorship of the Signal Corps. Some of this was done in conjunction with the development of new electronic equipment for the purpose of optimizing materials for a specific application; in several other instances, ferrite studies formed only a relatively small part of a broad over-all research program. In many contracts of this nature, the Signal Corps participated only as a co-sponsor, together with other branches of the Armed Services.

Our discussion will therefore be limited to tasks originated as part of the Signal Corps Electronic Materials Program for the specific purpose of the development of ferrite materials for military uses. A listing of the contractors participating in this work is given in Table I. Our discussion will be divided into four major sections arranged in the order in which projects in these areas were established, namely: 1) RF and VHF

TABLE I

SIGNAL CORPS CONTRACTS ON MAGNETIC FERRITE MATERIALS

Contractor and Location	Contract Number	Active Since
Indiana General Corp. General Ceramics Div. Keasbey, N. J.	W 36-039 sc-38239 DA 36-039 sc-5449 sc-56773 sc-71150 sc-74969	April, 1949
North American Philips Co., Inc. Philips Labs. Div. Irvington-on-Hudson, N. Y.	DA 36-039 sc-42503 sc-56759 sc-72319 sc-73223 sc-78071 sc-85279	July, 1952 May, 1956
General Electric Co. Syracuse, N. Y.	DA 36-039 sc-64696 sc-74904	June, 1955
Trans-Tech, Inc. Rockville, Md.	DA 36-039 sc-73124 sc-78907	December, 1956
Radio Corp. of America RCA Labs. Princeton, N. J.	DA 36-039 sc-78288	March, 1959

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.
[1] J. L. Snoek, "New Developments in Ferromagnetic Materials," Elsevier Publishing Co., Inc., New York, N. Y.; 1947. (Second Ed., 1949.)

materials, 2) square hysteresis loop materials, 3) permanent magnet materials, and 4) microwave and millimeter wave materials.

RF and VHF Materials

When samples of the first ferrite materials became available for evaluation by the Signal Corps, their shortcomings for use in military equipment were readily apparent. Their permeability varied strongly and in a complex manner with temperature, and their losses were found to become prohibitive at the higher frequency bands of military radio communication. The first development contract devoted to the search for new or improved ferrite materials for military applications went into effect with the General Ceramics and Steatite Corporation (now the General Ceramics Division of the Indiana General Corporation) in April, 1949. When some of the initial results of this work were published later that year, the paper became the first account of ferrite studies conducted in this country [1].

Some valuable lessons were learned from attempts to utilize the early materials in developmental equipment, even though more than once their initial success was tempered by serious subsequent difficulties. In one instance, "incremental permeability tuning" of wide-band panoramic sweep receivers by means of ferrite cores proved to be incomparably superior to the previous technique using motor driven capacitors [8]. Bandwidth, tuning rate, noise figures, power requirements, size, and weight of the equipment were all improved by orders of magnitude. A particularly gratifying side result was the finding that, in general, the losses decrease with increasing biasing field, thereby not only permitting excellent tuning ratios, but also extending substantially the upper frequency limit of operation. One material was found to perform with very creditable Q values up to 50 Mc in the biased condition, while it would not be satisfactory beyond a few megacycles in the normal demagnetized mode of operation.

The second instance where ferrites proved their superior potential occurred during the development of a high-precision permeability-tuned oscillator for use in several Signal Corps transmitters and receivers. In this case, the selection of the ferrite was mainly governed by concurrent requirements of high permeability and low temperature coefficient. Here, too, it was clearly established that the advanced design goals for this tuning oscillator could only be met by using a ferrite material.

In both of these cases, the difficulties alluded to above followed on the heels of the initial success. They were caused by the lack of experience with these materials on the part of the manufacturers, as well as on the part of the user. The quality level and tolerances of these materials had never been established, because they had never been made in real production quantities. The designers, on the other hand, had tried to squeeze the last bit of performance out of the samples with which they worked, obviously assuming that every piece of ferrite used later in production would be an exact duplicate in every respect of the few which they had used before.

Stimulated by these serious difficulties, a considerable amount of effort under the General Ceramics contract was spent to ascertain the effect of some major manufacturing variables, such as impurities, calcining methods, particle size, molding pressure, firing cycle, and others, upon the significant characteristics of the finished material. This study did not yield the solution for the reproducibility problem. It is certainly true that since this time the quality level of ferrites has greatly improved; the growing backlog of experience, the continuous evolution of new and better production techniques and equipment, and the strong forces of design requirements and competition have helped to bring about this progress. It is also believed true, however, that the ceramic process inherently entails such an inordinate number of critical conditions that even if their optimum parameters were fully known, they could not possibly be controlled individually and simultaneously. The diagnosis of "unassignable causes" for variations occurring in the final product of the ceramic process is therefore likely to remain with us for quite some time to come, and the same must be expected for the variations themselves.

To appraise this situation realistically by no means implies pessimism about the usefulness of the ferrites. The best proof to the contrary is that thousands of Signal Corps radio receivers and transmitters, now in actual field service, contain the very same incremental permeability tuners and precision tuning oscillators mentioned above for their early troubles. It is particularly gratifying to note that none of their original performance goals had to be abandoned.

The over-all status of the development of RF and VHF materials at present can best be discussed with the aid of Fig. 1. The top curve shows the "quality factor" $\mu_0 Q$ vs frequency. It begins with a value of about 500,000 at 0.1 Mc. This material is an experimental manganese-zinc ferrite. Its combination of very high initial permeability (2000) and Q (250) is the recent result of a rather extensive study of these compounds. The continuation of this curve from 1 Mc to 500 Mc represents several grades of nickel-zinc ferrites with small additions of cobalt [37]. This series of materials had its beginnings in 1953, when the uniquely beneficial effect of the cobalt addition was established in the laboratory of an affiliate of General Ceramics, the German Steatit-Magnesia Company. One of the more interesting devices which became possible by virtue of the extremely low losses and high permeability of these types of materials is a novel type of delay line conceived several years before by Golay,[2] but now built for the first time under his guidance by Elders [20] and, in another version, by Kulman [26].

[2] M. J. E. Golay, "The ideal low-pass filter in the form of a dispersionless lag line," Proc. IRE, vol. 34, pp. 138–145; March, 1946.

The exceptional Q values of these bodies are believed to be due to the reversible nature of their magnetization in the low field region, which is clearly evident in the linearity of the innermost hysteresis loop shown in Fig. 2. It goes hand in hand with the unusual "constricted" shape of the major loops shown in the same figure. Since this linearity extends to relatively high induction values of the order of 100 gauss or more, it appeared worthwhile to evaluate these materials for use in RF power transformers. A special measurement method was devised for this purpose [29], and results are shown for three different materials in Fig. 3. The operating induction at which the power losses reach 0.5 watt/cm³ has been cross-plotted in Fig. 1. The shaded area above this curve indicates the power rating of transformers which can be built [19] with these materials. Since this depends on a number of design considerations, the area reflects only an estimate, which is believed to be rather conservative. Such transformers have actually been built for the purpose of matching RF transmitters to their antenna; an example is shown in Fig. 4.

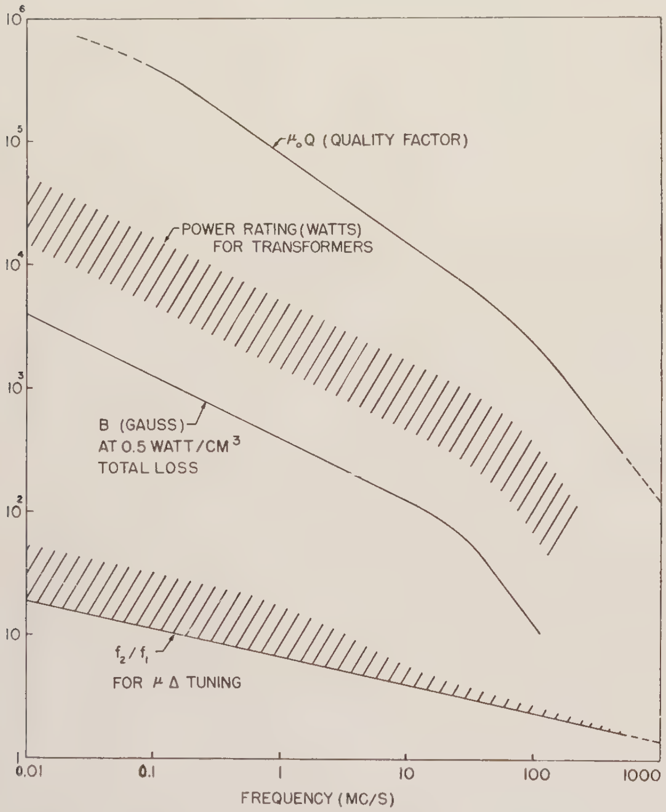

Fig. 1—RF and VHF properties of ferrite materials.

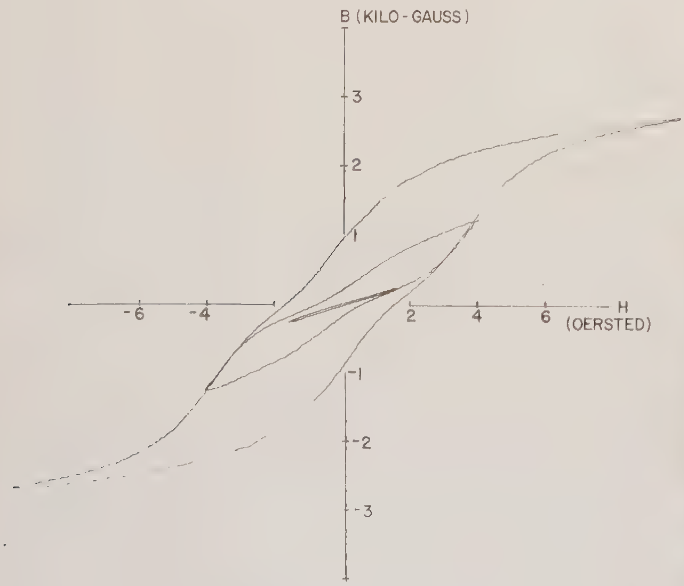

Fig. 2—Series of major and minor hysteresis loops of a nickel zinc (cobalt) ferrite—MF 2017-C.

The cross-hatched band at the bottom of Fig. 1 indicates the tuning ratios which can be achieved with presently available materials by using the incremental permeability tuning technique mentioned above. It can be seen that this technique is now practical up to almost 500 Mc.

The almost complete coverage of the RF and VHF range shown in Fig. 1 has resulted from work under the General Ceramics contracts listed in Table I. At present, there are two major tasks remaining, on which further work is continuing: 1) the improvement of the temperature stability of initial permeability, and 2)

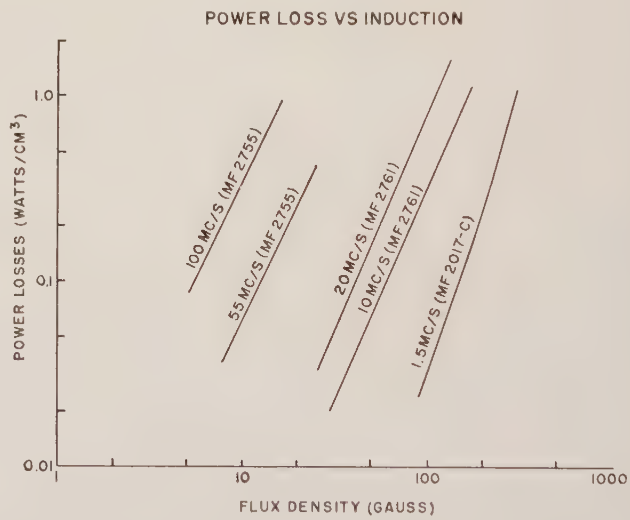

Fig. 3—Power loss vs flux density at several frequencies for a series of nickel-zinc (cobalt) ferrites.

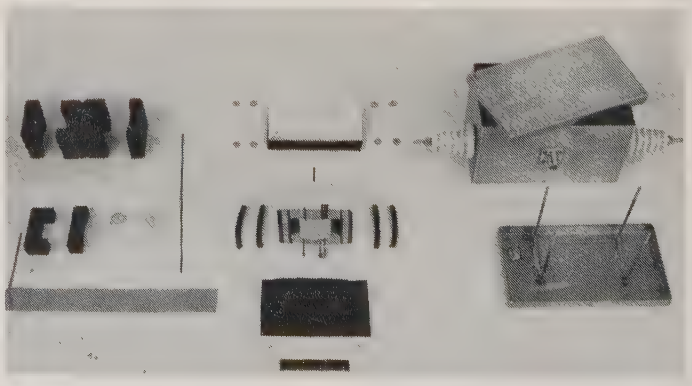

Fig. 4—Broad-band RF transformer (development model, 1955).

the further improvement of $\mu_0 Q$ and incremental tuning ratio in and above the VHF range. Some promising results on the first of these tasks have been obtained in the manganese-zinc ferrite group. An example is body MF 4373, whose $\Delta\mu_0$-vs-t curve is compared with that of another commercial grade of the same family in Fig. 5; both bodies have a permeability of about 1000. This improvement was mainly achieved by adjustment of composition and firing conditions. A different approach to this problem is being followed as part of the internal Signal Corps program. It consists in preparing the ferrite in the form of particles of extremely fine size, and in preventing their growth during subsequent preparation steps. Encouraging results have been obtained by this technique on a stoichiometric nickel ferrite [41].

Work on the second task, *i.e.*, the development of materials for the VHF range, constitutes a major part of the studies on hexagonal planar anisotropy compounds carried out under contract with the RCA Princeton Laboratories. The incremental permeability characteristics of these materials appear to be particularly promising. At 250 Mc, one experimental body shows a "remanent state" permeability of 15 which changes to a value of 5.3 by application of a bias field of only 40 oersteds. The Q value stays above 45 over this range. This is considerably better than the best competitive values offered by spinel type ferrites. It is therefore believed that the hexagonal planar ferrites may also become very useful for phase shifters in the UHF range.

Square Hysteresis Loop Materials

In its over-all program on magnetic materials, the Signal Corps was already actively engaged in work on square hysteresis loop materials of the metallic variety (nickel-iron, cobalt-iron and other alloys) before the first ferrites came along. The first observation of a pronounced "break" in the hysteresis loop of a ferrite was made at the Signal Corps in October, 1948.

The material in question was a magnesium-manganese body chosen as a high frequency material by General Ceramics because of its high volume resistivity. An oscilloscope trace, also showing the comparative squareness of its hysteresis loop, was shown in the paper mentioned above [1].

In 1950, a sample of this material was furnished by General Ceramics to the Servomechanism Laboratory of M.I.T. for comparison with a number of metallic square loop materials with respect to its potential usefulness in the coincident current memory system devised by Forrester[3] for the Whirlwind I computer. In spite of its low saturation, its high coercive force and its rather poor loop squareness, the ferrite sample attracted immediate interest because of its much superior switching speed.

[3] J. W. Forrester, "Digital information storage in three dimensions using magnetic cores," *J. Appl. Phys.*, vol. 22, pp. 44–48; January, 1951.

The development of ferrites with improved loop rectangularity became, therefore, a part of the Signal Corps contract with General Ceramics. By 1951, some progress had been made, and the feasibility of their use in the coincident current memory was firmly established. Later that year, further experiments yielded the first compounds possessing B_r/B_s ratios exceeding 0.9 and coercive force values of less than 1 oersted [5], [13], [24]. Early in 1952, the prototype of memory core materials, body MF 1118, was placed on the market by General Ceramics. The hysteresis loop of this body is compared with that of the original material in Fig. 6. Several months later, the company entered a direct contract with M.I.T. for the purpose of further production refinement, particularly with respect to reproducibility and quality control. At this point, the Signal Corps discontinued its sponsorship of this task. (The first 17,000-bit memory using the General Ceramics material, now known as Ferramic S-1, was successfully completed by M.I.T. in the summer of 1953.)

Permanent Magnet Materials

Under the threat of a severe shortage of cobalt and nickel brought on by the greatly increased requirements

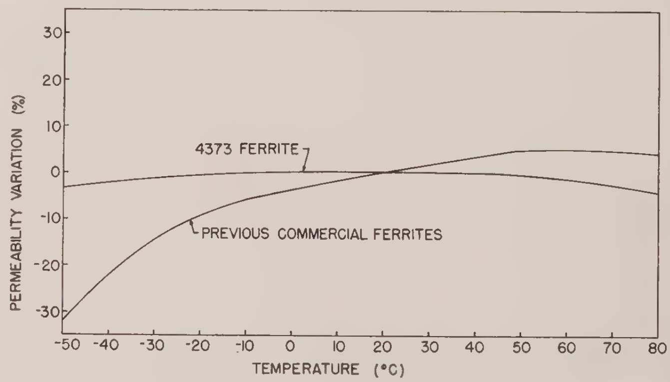

Fig. 5—Temperature stability of initial permeability of manganese-zinc ferrites.

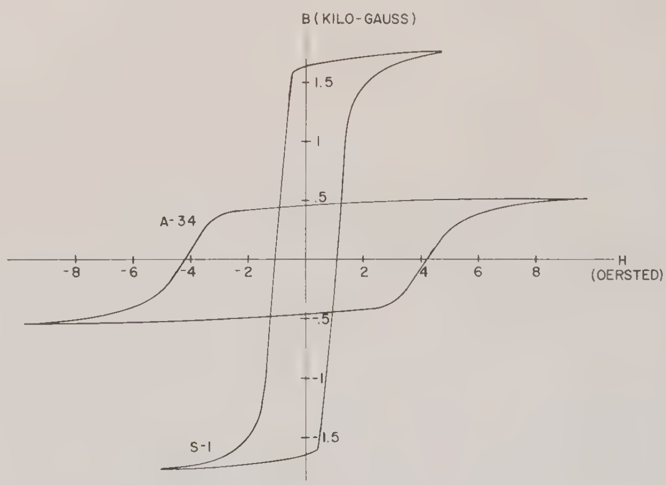

Fig. 6—Square hysteresis loop ferrites.

for "super-alloys" during the Korean conflict, nonstrategic substitutes for the permanent magnet material Alnico V were urgently sought for military use, as well as for the rapidly expanding TV industry. The Signal Corps selected the pursuit of further work on the newly announced barium ferrite permanent magnet material[4] as the most promising means to alleviate the shortage expeditiously. In July, 1952, work began at the Philips Laboratories Division of the North American Philips Company to determine the optimum preparation techniques for the hexagonal barium and strontium ferrites.

The first phase of this work was only concerned with the randomly oriented material, stressing mainly the steps leading to the required single domain particle size and the final firing procedure. In the second phase, the factors governing the degree of orientation[5] and the attendant improvement of the energy product were studied, and in 1954, this work succeeded with the preparation of samples having an energy product of 3.5×10^6 gauss-oersted. A demagnetization curve of this material is shown in Fig. 7, which is taken from the final report by Philips Laboratories.

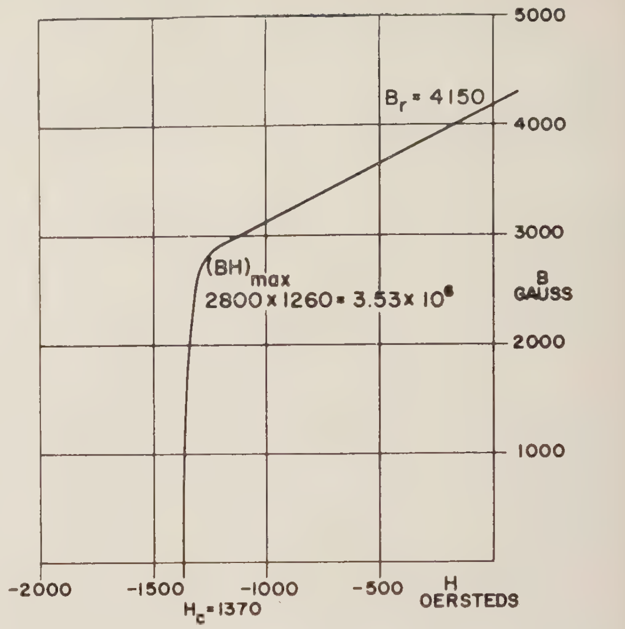

Fig. 7—Demagnetization curve of oriented barium ferrite.

While the immediate need for these materials had subsided with the cessation of hostilities in Korea, their adoption on a rather large commercial scale came about later on the basis of their technical and economical merit. At that time, the spade work done under the Signal Corps contract proved very helpful to the prospective manufacturers.

Microwave and Millimeter Wave Materials

In the early 1950's, the results of theoretical and experimental studies of resonance phenomena and Faraday rotation were translated into devices for controlling the transmission of microwave energy by means of these effects. The first practical device of this type, the Luhrs[6] microwave switch, was made with the same General Ceramics material which had previously attracted attention for its square loop characteristics. This led to a very active search for optimized microwave ferrite materials, particularly in the mixed magnesium-manganese ferrite system. General Ceramics conducted such studies under an equipment sub-contract sponsored by the Bureau of Aeronautics of the Department of the Navy, beginning in 1953 [13].

Meanwhile, the Signal Corps co-sponsored a contract let by the Bureau of Ships, Department of the Navy, to the Bureau of Mines, College Park, Md. This group prepared numerous experimental compounds. These were screened by the Signal Corps, mainly with respect to their merits for use at high power levels [11], [16], and some of these were made available to the Signal Corps contractors for use in experimental or prototype microwave devices.

Similar studies were continued later under Signal Corps contracts with Trans-Tech, Inc., in Rockville, Md. [22].

At the medium and high power levels of microwave energy used in many radar equipments, the ferrites were found to undergo a severe degradation of their resonance characteristics. A Signal Corps contract was therefore let with the General Electric Company, Syracuse, N. Y., in 1955, for the purpose of studying this effect and developing materials which would sustain operation at kilowatt average and megawatt peak power levels, particularly at S-band frequencies.

The work was mostly devoted to magnesium and nickel ferrite compounds modified by partial substitutions of the ferric oxide by alumina. Two compounds encountered in this work showed excellent low power microwave characteristics at S- and C-band frequencies. Two related bodies were found which are able to operate with minimum degradation at moderate power levels at the same frequencies [23].

Another approach envisages the prevention of the main resonance degradation by reducing the effective crystallite size of the ferrite grain to a level where it would be very small in comparison with the spin wavelength. This work is still in progress.

Another objective of the Signal Corps microwave ferrite program is the extension of the frequency coverage into the centimeter and millimeter wave region. The approach to this problem is based on the extremely high values of anisotropy fields available in the hexagonal ferrite compounds. These built-in anisotropy fields can be substituted for external magnets which would other-

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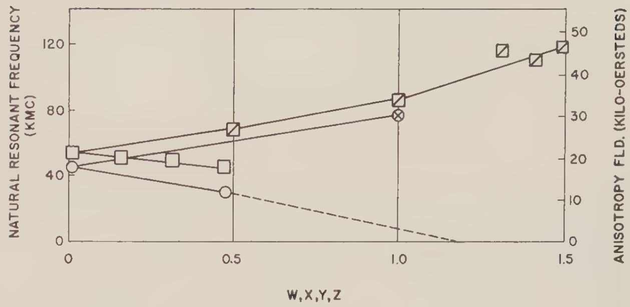
[6] Built by C. H. Luhrs and Co., Hackensack, N. J.

wise be required to achieve gyromagnetic resonance. This is particularly desirable where the field strength needed becomes very large: for 30 kMc the required resonance field exceeds 10,000 oersteds, for 140 kMc it is 50,000 oersteds. On the basis of the previous work devoted to hexagonal ferrites for permanent magnet applications, a new contract was let with the Philips Laboratories for studying the possibility of adjusting the anisotropy field strength of these compounds by modification of the composition [30], [31]. It was found that anisotropy values up to 45,000 oersteds can be achieved by replacing about one-fourth of the ferric oxide in this compound by alumina. On the other hand, it is also possible to reduce the anisotropy field to relatively low values by substituting a fraction of ferric oxide by a combination of titanium and cobalt oxides. The anisotropy fields and the resultant "natural" resonance frequencies are shown as a function of these substitutions in Fig. 8.



○ $(BaO)_{1.1} \cdot [(TiCo)O_3]_W \cdot (Fe_2O_3)_{(6-W)}$
⊗ $(BaO)_{1.1} \cdot (Al_2O_3)_X \cdot (Fe_2O_3)_{(6-X)}$
⧄ $(SrO)_{1.1} \cdot (Al_2O_3)_Y \cdot (Fe_2O_3)_{(6-Y)}$
□ $(SrO)_{1.1} \cdot [(TiCo)O_3]_Z \cdot (Fe_2O_3)_{(6-Z)}$

Fig. 8—Effect of substitutions on the natural resonant frequency and anisotropy of barium and strontium ferrites.

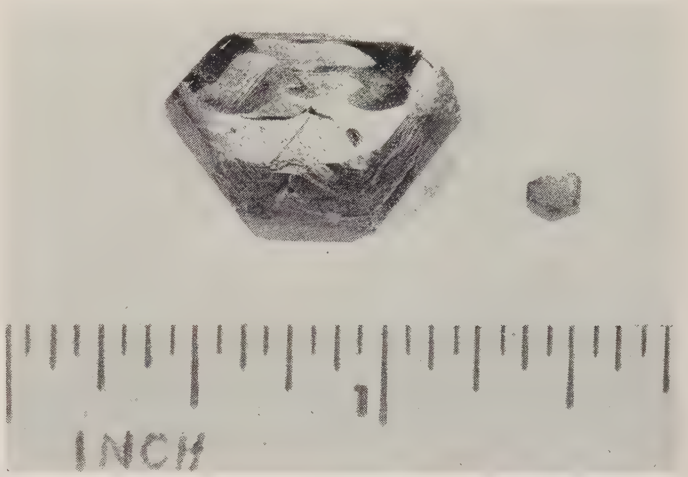


Fig. 9—Single crystal of barium ferrite, left, and of Zn_2Y, right.

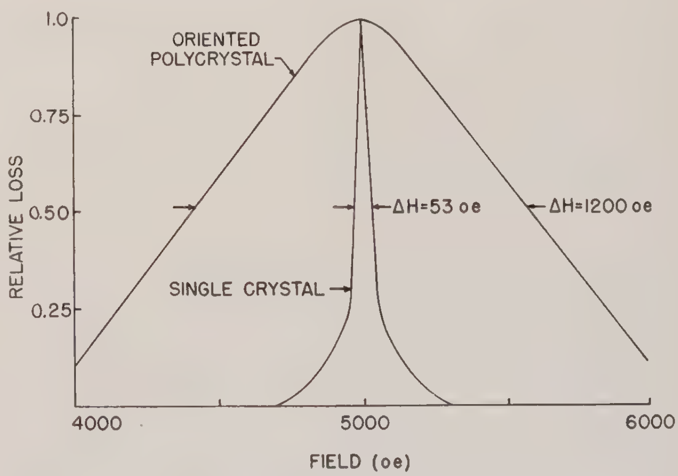


Fig. 10—Line width of single crystal and oriented polycrystalline barium ferrite.

Even in well-oriented polycrystalline samples, the microwave behavior of these materials, particularly their resonance line width, is still rather poor. It is therefore interesting to note that unusually sharp lines have been obtained from measurements of single crystals of at least two of these compounds. The single crystal of barium ferrite grown in the Signal Corps laboratory [32] is shown in Fig. 9; its resonance line is compared with that of oriented polycrystalline material in Fig. 10, as measured at about 55 kMc [38]. The line width of 53 oersteds found for this single crystal is in agreement with a similar measurement made by Philips Laboratories on an alumina substituted barium ferrite single crystal which they had obtained from the Dutch Philips Company.

On the basis of these results, there is considerable hope that with further refinement of the orientation technique or with the availability of a sufficient selection of compositions in single crystal form, the whole millimeter wave region will be adequately covered by self-resonant narrow-line-width materials.

It is even conceivable that these materials may invade the X- and S-band region which up to now has been the domain of the spinel and garnet type materials; size reduction or elimination of external field magnets for devices operating at these frequencies would be a strong argument in favor of the hexagonal ferrites.

It was mentioned above in discussing VHF materials that hexagonal ferrites with planar anisotropy are being studied under a Signal Corps contract with RCA Princeton Laboratories. The compounds prepared under this contract are also being evaluated with respect to their microwave characteristics. Oriented planar materials having a line width as low as 200 oersteds have been obtained. These materials are of interest in microwave devices since, due to their high planar anisotropy, less biasing field is required for resonance than for regular spinel type ferrites, and a degree of broad banding is obtained [36].

The relatively high anisotropy values of the planar ferrites may also offer significant improvements in nonlinear devices, particularly for harmonics generation. This expectation is based on a theoretical analysis [36] showing that under certain conditions the efficiency of harmonics generation is proportional to the sum of the saturation magnetization and the anisotropy field,

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New Trends in Signal Corps Transistor Development*

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Summary—**Signal Corps transistors are discussed with special emphasis on device developments during the last five-year period. A generic development is presented starting with germanium and silicon alloy-junction transistors and leading to germanium and silicon diffused junction-type devices that reflect the extended frequency and power capability of the transistor. Devices developed under Signal Corps contracts are described and the importance of these new transistors for military and industrial use is illustrated. In addition, a graphic picture of the growth of the Signal Corps developments is included.**

Introduction

A FEW YEARS AGO it was not uncommon to find the familiar sign "Help Stamp Out Transistors" displayed in many circuit design laboratories. Along with this approach, there were more serious allegations made against the use of the transistor. The transistor industry has hurdled a long line of obstacles and advanced far beyond what was expected back in the early days of development. A major share of this development has resulted from Signal Corps sponsorship and funds. The specific measure taken by the Signal Corps to accomplish this end was the Industrial Preparedness Measures Program, more recently named Production Engineering Measures (PEM). Briefly, these measures were initiated to assure availability of specific military items and, if necessary, to negotiate a contract with qualified producers to perform in accordance with Signal Corps industrial preparedness procurement requirements.

The purpose of this paper is to indicate the latest transistor developments that have occurred under the PEM programs since the beginning of FY-1956. It would be useful, however, to review the accomplishments of the program prior to that time.

In FY-1952, development of the following low-power germanium alloy-junction transistors was sponsored: 2N43, 2N44, 2N64, 2N65, 2N34, 2N35, and 2N96. These transistors are still available with the exception of the 2N96 which was replaced by the 2N331. (Only the outside case of the 2N96 was changed.) These devices are characterized basically as audio devices with alpha-cutoff frequencies of approximately 0.5 to 1.0 megacycles per second. At that time germanium alloy-junction transistors were in the early development stage.

In FY-1954, the frequency and power capabilities of germanium devices were improved by the inclusion of the 2N297 power transistor and a group of surface-barrier transistors: 2N128, 2N299, and 2N300. The latter group of germanium surface-barrier devices was characterized in terms of maximum frequencies of oscillation between 60 and 100 megacycles per second. At that time the surface-barrier family of devices upheld the frequency spectrum of the transistor art.

In FY-1955, the Signal Corps, recognizing the need for silicon devices, sponsored activity of both alloy- and grown-junction silicon transistors, and this led to the development of the 2N327A, 2N328A, and 2N329A devices, along with tetrode grown-junction devices such as the 3N24 and 3N28. The former group of silicon units is characterized as an audio device with alpha-cutoff frequency between 0.2 and 0.5 megacycles per second. At this point it appeared that the transistor had reached its first plateau of development in terms of frequency capability. What was needed was a major breakthrough in device technology and this occurred during the latter part of 1955 with the announcement by the Bell Telephone Laboratories of the diffusion process for transistor fabrication. The Signal Corps realized that with this new process a host of new devices could be fabricated in both germanium and silicon material and that transistors necessary for equipment development would become available.

What follows are the results of the PEM program, indicating the significant advancements made.

Significant Advances in Transistor Development

The Signal Corps established a list of required devices impossible to achieve before existence of the diffusion process for transistor fabrication. On the basis of these requirements, the FY-1956 Transistor PEM Program was initiated. Its scope is reflected in Table I which

TABLE I
Scope of FY-56 PEM Program

Contractor	No. of Device Developments
Transitron Electronic (Wakefield, Mass.)	7
RCA (Somerville, N. J.)	7
Lansdale Tube Co. (Lansdale, Pa.)	6
Sylvania Electric (Woburn, Mass.)	6
Motorola Inc. (Phoenix, Ariz.)	3
Texas Instruments. (Dallas, Tex.)	3
Western Electric (New York, N. Y.	2
Raytheon Manufacturing Co. (Newton, Mass.)	2
Hughes Aircraft (Newport Beach, Calif.)	2
Total 9	38

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.
‡ U. S. Army Signal Supply Agency, Philadelphia, Pa.

TABLE II

DEVICES DEVELOPED UNDER FY-56 PEM PROGRAM

Company	Device Designation	Material	Polarity	Application	Power Dissipation	Frequency Response	Fabrication Technique
TRANSITRON ELECTRONIC	2N1079	Si	*n-p-n*	high power	30 watts @ 25°C case temperature	10 Mc f_t	DBT
	2N1080	Si	*n-p-n*	high power	60 watts @ 25°C case temperature	10 Mc f_t	DBT
	2N1081	Si	*n-p-n*	0.5 a switch	4 watts @ 25°C case temperature	$t_r+t_s+t_f=1.2$ μsec	GD
	2N1082	Si	*n-p-n*	4.3 Mc-20 db a	0.2 watt @ 25°C ambient	16 Mc f_t	GD
	2N1083	Ge	*p-n-p*	0.5 a switch	1.25 watts @ 25°C case temperature	$t_r+t_s+t_f=1.5$ μsec	A
	2N1084	Si	*p-n-p*	medium power	5 watts @ 25°C case temperature	10 Mc f_t	DBT
	2N1085	Si	*n-p-n*	medium power	5 watts @ 25°C case temperature	10 Mc f_t	GD
RCA	2N1001	Ge	*p-n-p*	medium power audio	7.5 watts @ 25°C case temperature	0.5 Mc f_α	A
	2N1002	Ge	*n-p-n*	medium power audio	3.75 watts @ 25°C case temperature	0.5 Mc f_α	A
	2N1067 & 8	Si	*n-p-n*	medium power audio	10 watts @ 25°C case temperature	0.5 Mc f_α	DEC
	2N1069 & 70	Si	*n-p-n*	high power audio	55 watts @ 25°C case temperature	0.5 Mc f_α	DEC
	2N1368 & 9	Si	*n-p-n*	medium power audio	4 watts @ 25°C case temperature	0.5 Mc f_α	DEC
	Device 13	Si	*p-n-p*	medium power audio	4 watts @ 25°C case temperature	0.4 Mc f_α	DEC
	Device 14	Si	*p-n-p*	medium power audio	12 watts @ 25°C case temperature	0.5 Mc f_α	DEC
LANSDALE TUBE CO.	2N501A	Ge	*p-n-p*	high-speed switch	60 mw @ 25°C ambient temp.	$t_r+t_s+t_f=47$ mμsec	MADT
	2N502A	Ge	*p-n-p*	200 Mc-9.5-db a	60 mw @ 25°C ambient temp.		MADT
	2N1158A	Ge	*p-n-p*	200 Mc oscillator	60 mw @ 25°C ambient temp.		MADT
	2N1199A	Si	*n-p-n*	high-speed switch	100 mw @ 25°C ambient temp.	$t_r+t_s+t_f=1.05$ μsec	SADT
	2N1200	Si	*n-p-n*	4.3 Mc-20-db a	100 mw @ 25°C ambient temp.	25 Mc f_t	SADT
	2N1201	Si	*n-p-n*	12.5 Mc-20-db a	100 mw @ 25°C ambient temp.	30 Mc f_t	SADT
SYLVANIA ELECTRIC	2N1001	Ge	*p-n-p*	medium power audio	7.5 watts @ 25°C case temperature	0.5 Mc f_α	A
	2N1002	Ge	*n-p-n*	medium power audio	3.75 watts @ 25°C ambient temp.	0.5 Mc f_α	A
	2N624	Ge	*p-n-p*	12.5 Mc-20-db a	100 mw @ 25°C ambient temp.		D
	2N625	Ge	*n-p-n*	0.5 a switch	1.25 watts @ 25°C case temp.	$t_r+t_s+t_f=1.5$ μsec	A
	Device 13	Si	*p-n-p*	medium power audio	2 watts @ 25°C case temp.		DEC
	Device 13	Si	*n-p-n*	medium power audio	2 watts @ 25°C case temp.		DEC

TABLE II (*cont'd*)

Company	Device Designation	Material	Polarity	Application	Power Dissipation	Frequency Response	Fabrication Technique
MOTOROLA	2N1003	Ge	*p-n-p*	12.5 Mc-20-db a	120 mw @ 25°C ambient temp.		D
	2N700	Ge	*p-n-p*	70 Mc-24-db a	75 mw @ 25°C ambient temp.	280 Mc f_t	DBT
	2N1004	Ge	*p-n-p*	video amplifier	120 mw @ 25°C ambient temp.		D
TEXAS INSTRUMENT	2N702	Si	*n-p-n*	high-speed switch	600 mw @ 25°C ambient temp.	70 Mc f_t	DBT
	2N716	Si	*n-p-n*	70 Mc power oscillator & amplifier	600 mw @ 25°C ambient temp.	70 Mc f_t	DBT
	3N35	Si	*n-p-n* (tetrode)	70 Mc-15-db a	125 mw @ 25°C ambient temp.	70 Mc f_t	GD
WESTERN ELECTRIC	2N537	Ge	*p-n-p*	200 Mc power oscillator	225 mw @ 25°C ambient temp.	200 Mc f_t	DBT
	2N694	Ge	*p-n-p*	70 Mc-18-db a	100 mw @ 15°C ambient temp.	300 Mc f_t	DBT
RAYTHEON	Device 15	Si	*n-p-n*	high power audio	55 watts @ 25°C case temp.	2.0 Mc f_α	DBT
	Device 25	Si	*n-p-n*	video amplifier	150 mw @ 25°C ambient temp.	30 Mc f_α	DBT

Legend:

Materials
Ge—germanium
Si—silicon

Fabrication Technique
DBT—Diffused Base Transistor
GD—Grown Diffused
A—Alloy
DEC—Diffused Emitter Collector
D—Drift
MADT—Micro Alloy Diffused Transistor
SADT—Silicon Alloy Diffused Transistor

TABLE III
DEVICE OBJECTIVES OF THE FY-59 PEM PROGRAM

Contractor	Material	Polarity	Application	Power Dissipation	Fabrication Technique
TRANSITRON	Si	*n-p-n*	10-mc power oscillator & amplifier 5 watts RF power output	17.5 watts < 25°C case temperature	DBT
MOTOROLA	Ge	*p-n-p*	70-mc power amplifier & oscillator 1 watt RF power output	3. 5 watts < 25°C case temperature	DBT
RCA	Si	*n-p-n*	70-mc power amplifier & oscillator 1 watt RF power output	3.5 watts < 25°C case temperature	DBT

gives the names of the companies and the number of devices each developed. Table II lists the devices that each company developed or is developing, the semiconductor material used, the general device design, and some of the important technical characteristics. It is evident from this compilation that the FY-1956 program has yielded devices of greater frequency capability than previously considered possible with germanium devices and that both the power and frequency capabilities of silicon devices have been greatly improved.

All of the devices specified in the FY-1956 program were not funded at that time because the technical approaches of the contractors were not feasible. With the rapid strides accomplished in the FY-1956 program, however, the questionable devices became more of a reality. As a result, the FY-1959 Transistor PEM Program was initiated which was a logical extension of the FY-1956 effort. This is illustrated in Table III which lists the objectives of the FY-1959 program and indicates the developments aimed at improving the frequency and power capabilities of both germanium and silicon.

Advancements made as a result of these programs are shown in Figs. 1 and 2. Fig. 1 is a germanium device

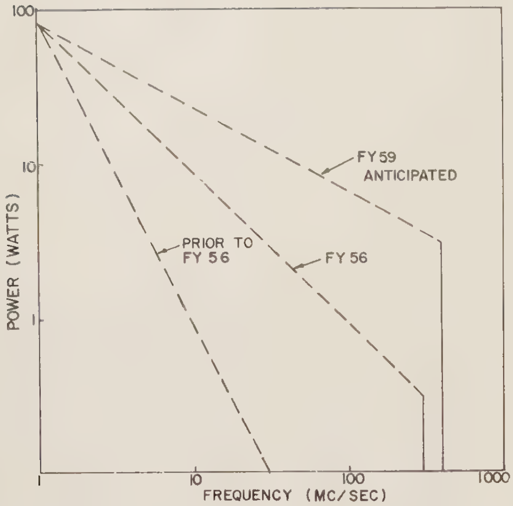


Fig. 1—Germanium device progress chart.

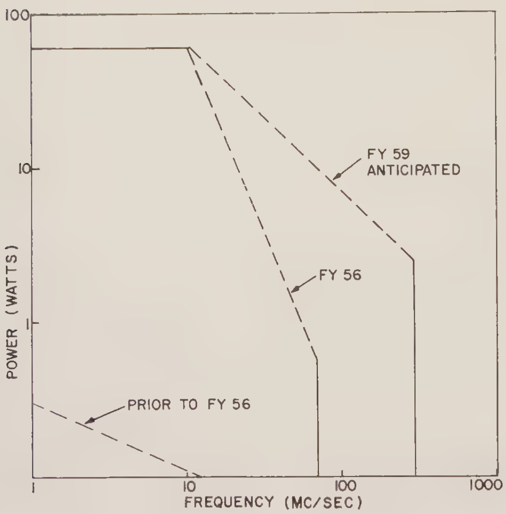


Fig. 2—Silicon device progress chart.

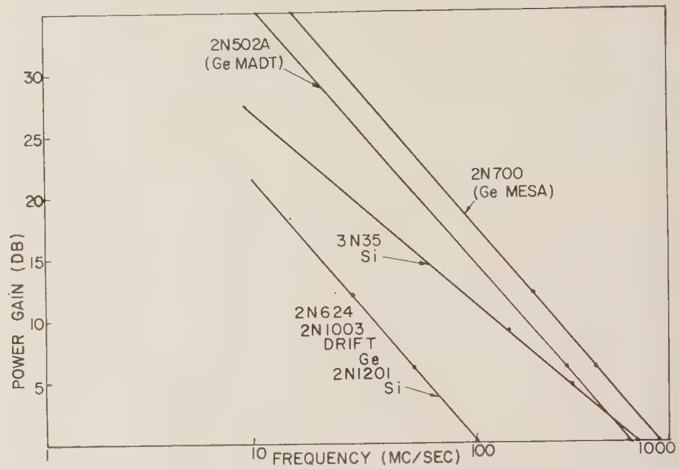


Fig. 3—Matched neutralized power gain vs frequency.

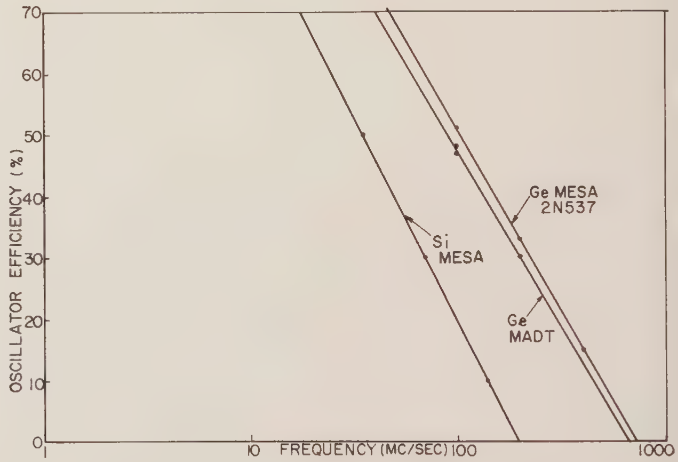


Fig. 4—Oscillator efficiency vs frequency.

progress chart. The ordinate of the graph represents the power capability of the device; the abscissa represents either the alpha cutoff, f_α, or gain equal unity frequency, f_t. The broken lines are used only to connect the known terminal points. Indicated also is the growth in the frequency power curve of the germanium devices in terms of the advancements made during FY-1956 and -1959. The tendency is for the broken portion of the curve to become more and more parallel with respect to the abscissa. In a similar manner Fig. 2 represents the progress made by silicon devices. Here the advancements made by the two programs are more pronounced. The same conclusion, however, is reached; *i.e.*, the broken portion of the curve appears to be approaching a line parallel to the abscissa, indicating the enhancement of frequency power capabilities of transistors.

To provide more significant engineering data, Fig. 3 represents a plot of the matched neutralized power gain as a function of frequency for some select amplifier structures developed under the program. These curves represent the minimum gain to be expected from the devices. The curves are based on a 6 db per octave falloff of power gain with frequency on all structures except the tetrode where a 4.5 db per octave is assumed. If it is assumed that 6 db represents a usable power gain, then the germanium mesa transistor will operate at about 500 megacycles per second and the MADT and tetrode transistors at about 300 megacycles per second. At the beginning of the program, usable gains were experienced up to about 10 megacycles per second with available structures. It can be stated that the frequency capability of transistors has been increased by more than an order of magnitude.

Fig. 4 is a plot of the oscillator efficiency vs frequency for some select oscillator devices developed under the FY-56 program. The rate of falloff with frequency was determined, based on empirical studies made at the

U. S. Army Signal Research and Development Laboratory. From Figs. 3 and 4, it is evident that the maximum frequency of oscillation of typical units has reached the one-kilomegacycle frequency. Comparing this with units available before the program was started shows that the usable frequency capability in terms of the maximum frequency of oscillation has increased by greater than an order of magnitude.

Equipment Development

The aim of the PEM program has been to supply new devices to the military agencies or their contractors in order to enhance development and production of new equipment. This has been accomplished. Some of the highlights of Signal Corps equipment developments based on the availability of these new transistors are shown in Table IV. Transistors are presently being utilized in hundreds of military equipment developments including radar, communication, telephone, teletype, computer, power sources, missiles, and satellite systems.

TABLE IV

Highlights of Signal Corps Equipment Developments Utilizing Devices Developed Under the FY-1956 PEM Program

Equipment Title	Nomenclature
Radar Surveillance Set	AN/DPD-1
Flight Safety Receiver	AN/DRW-11
Radio Set	AN/GRC-59
Mobile Digital Computer (MOBIDIC)	AN/MSQ-20
Helmet Radio	AN/PRC-34, -36
Communication Set	AN/PRC-25, -35

Results

Aside from the prime purpose of the PEM program to make devices available for military equipment, the fact cannot be overlooked that the whole electronics industry has benefited. A minimum of sixty new devices developed by the industry-at-large up to the present time was made possible by the technical advances yielded under the FY-1956 and -1959 Transistor PEM Programs. Advancements should continue to be made under future programs.

Silicon Integrated Circuits*

WILLIAM B. GLENDINNING†, member, ire

Summary—**The use of semiconductor integrated circuitry to reduce size and weight of military electronic systems is discussed. The pure semiconductor integrated circuit approach used to obtain micro-microminiaturization levels is reviewed and characterized. Described in this paper are the design and construction of a silicon integrated microcircuit. Results of examination of the electrical performance of the microcircuit are presented, including results of examination of the thermal behavior of the microcircuit. The silicon structure is analyzed in terms of internal and external geometry, material properties, and electrical performance.**

Introduction

THE military need for increasingly smaller electronic components and electronic systems is perhaps more of a requisite now than ever before. Missile and outer space applications have focussed attention on the task of making smaller electronic systems. Many historic technical findings have caused electronic system miniaturization to advance in various directions. A few of the developments instrumental in directing the approaches to miniaturization were: Project Tinkertoy, stacked electronic tubes, tantalytic capacitors, film resistors, magnetic film devices, semiconductor devices, subminiature tubes, and printed circuits. As a result of these developments, the term "miniaturized" has been used for a long time to describe the status of military electronic systems.

The present status of the U. S. Army Signal Corps miniaturization efforts has already been described.[1] The level of miniaturization recently achieved by the Signal Corps has been termed "microminiaturized," and is characterized by component densities of 5×10^4 per cubic foot. Signal Corps electronic systems of this type (called "micromodularized") have resorted to extensive use of semiconductor devices, both diodes and transistors, in unpackaged form.

Many new results in the technical fields will cause an even greater degree of miniaturization to arise. Out of the maze of events affecting the nature of future electronic systems have come such terms as integrated microcircuitry, semiconcircuits, solid-state circuits, molectronics, phenomenological approach, molecular engineering, and angstronics. Technical efforts associated with these terms have two things in common: 1) they

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

[1] P. G. Jacobs, "Micromodule design progress," *Elec. Mfg.*, pp. 78-85; March, 1959 (reprint no. 736).

depend upon the use of semiconductor structures, and 2) they are directed towards the attainment of component densities of 5×10^5 to 1×10^6 components per cubic foot. The level now being sought is termed micromicrominiaturization.

Of the current approaches to micromicrominiaturization, many are worthy of continued investigation. The area described by names such as integrated microcircuitry, solid-state circuits, and semiconcircuitry, has already yielded useful results.[2–4] This paper deals with findings in the field of integrated microcircuitry—more particularly, with the semiconductor material silicon.

The integrated microcircuit approach has been inspired by the realization that semiconductor structures can be fashioned in such a way that regions yield capacitive and resistive effects. No longer is it necessary to make separate resistive or capacitive elements smaller. The pure semiconductor integrated microcircuit approach does not imply that distinctive semiconductor regions will be apparent to the aided eye, and will represent capacitors or resistors on a one-for-one replacement basis. The concept does imply, however, that resistive regions will take some form described by the expression

$$R = \int_a^b \frac{\rho(x)dx}{A(x)},$$

where R is resistance, ρ is resistivity, A is cross-sectional area, and dx is the incremental distance through the region.

The pure integrated microcircuit concept also requires the use of p-n junctions functioning as capacitive elements according to the expression

$$C = \frac{K}{(V_0 + V)^n},$$

where C is ac transition capacitance, K is an adjustive constant depending upon internal geometry, V is reverse bias voltage across the junction, V_0 is natural reverse bias, and n is an exponent which is determined by the internal geometric features of the junction.

The concept finally requires that external electrical contacts be kept at a minimum. To accomplish this, distributed resistances and distributed resistance-capacitance combinations are resorted to. Summarizing, the pure semiconductor integrated microcircuit approach is characterized by the following features:

1) Diodes, transistors, resistances, and capacitances are composed of, and united in one slab of, semiconductor material.
2) Resistive regions are composed of conductance channels, with conduction determined by free carrier concentrations and carrier mobilities.
3) Capacitive regions consist of reversed bias junction regions.
4) Undisturbed bulk semiconductor regions are used for electrical contact purposes wherever possible.

These features define the primary broad design boundaries of the approach.

The semiconductor microcircuit form assumes a specific geometric pattern (both internally and externally) as a result of the interdependencies of all of the design variables involved. A complex semiconductor slab-structure pattern is further governed by the electrical circuit function desired. There are no intermediate steps between active and passive element construction and the electronic microsystem. A completed electrical circuit exists immediately upon completion of a series of processes performed directly upon a slab of semiconductor material. Circuit performance is directly related to material and structure properties such as carrier mobilities, carrier densities, carrier lifetime, surface recombination velocity, and impurity densities. Since almost all of the basic properties are thermally sensitive, slab-structure pattern is also controlled by expected environmental and operating conditions.

In an effort to become further acquainted with the pure semiconductor integrated microcircuit field, an experimental program was initiated at the U. S. Army Signal Research and Development Laboratory. Availability of single-crystal silicon material, technology, and military application advantages of silicon influenced the selection of a slab material.

Experimental Results

A. General

A simple electrical circuit function was selected to simplify the fabrication requirements in making a silicon structure. The circuit chosen was to possess, as nearly as possible, the four characteristic features of the pure integrated microcircuit approach, and the circuit function selected was that of demodulation. As illustrated by the electrical circuit schematic in Fig. 1, a simple AM demodulator consists of a switching section (diode) and an energy storage and release section (capacitor-resistor combination). Also illustrated in Fig. 1 is a sketch representing the external geometric pattern of the structure devised to yield the desired electrical performance. To identify the electrical roles of the various slab regions, a schematic sketch was superimposed upon the sketch of the slab. One region performs the diode switching role, the second region performs the capacitive storage role, and the third performs the resistive dissipative role.

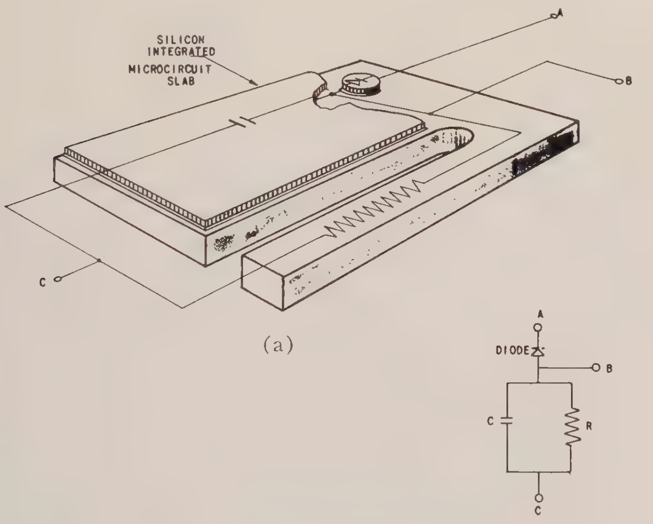
A detailed description of the structure is presented in Fig. 2. Selection of the over-all dimensions of the

[2] J. S. Kilby, "Semiconductor solid circuits," *Electronics*, vol. 32, pp. 110–111; August 7, 1959.
[3] J. T. Wallmark and S. M. Marcus, "Semiconductor devices for microminiaturization," *Electronics*, vol. 32, pp. 35–37; June 26, 1959.
[4] J. T. Wallmark and S. M. Marcus, "Integrated devices using direct coupled unipolar transistor logic," IRE Trans. on Electronic Computers, vol. EC-8, pp. 98–107; June, 1959.

structure was influenced by the present form of Signal Corps micromodularized electronic equipment. The present basic micromodule ceramic wafer dimensions are 0.310 by 0.310 inch. The microcircuit slab's over-all dimensions of 0.125 by 0.187 inch were considered to be compatible with micromodule dimension requirements. The region having a cylindrical appearance functions as a diode; the large rectangular parallelepiped-shaped region functions as a capacitive element; and the slender rectangular parallelepiped-shaped region functions as a resistive element.

Antimony diffusion was used in forming the 5-micron deep *n*-type surface layer in a *p*-type silicon substrate. The *p-n* junction, located 5 microns beneath the outer slab surface, easily permitted a diode and a capacitive region to be formed. Fig. 3 illustrates the slab's appearance during various phases of fabrication. In phase (a), the rectangular slab cut from a diffused silicon wafer is illustrated. The slab is completely masked with an asphalt material, and the silicon surface is scratched clean along a short line segment. The slab is immersed in CP_4 etch solution for eight minutes and upon removal it contains a slot as shown in phase (b). Asphalt masking material is again applied to desired surface locations, and the slab is reimmersed in a slow etch. Upon removal from the etch solution, the slab appears as illustrated in phase (c). A large rectangular shaped mesa and a small circular shaped one have been formed by the second etch. The final fabrication step consists of making electrical ohmic contacts to the four locations indicated in phase (d).

The photograph in Fig. 4 shows the appearance of a completed integrated microcircuit. The structure is mounted on a transistor stem.



(a) (b)

Fig. 1—(a) A superimposed circuit schematic showing a pure semiconductor integrated microcircuit and roles of regions. (b) Circuit schematic of a simple AM demodulator.

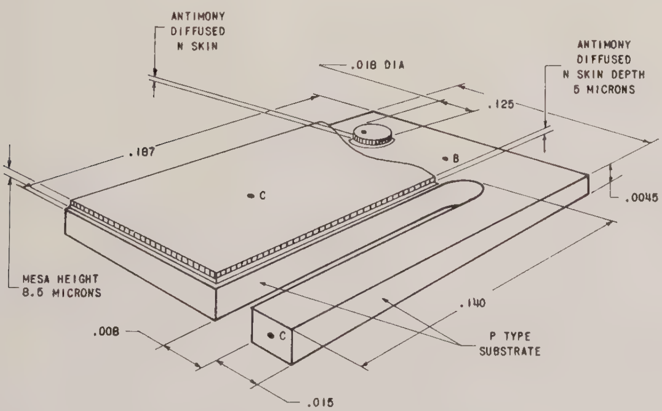
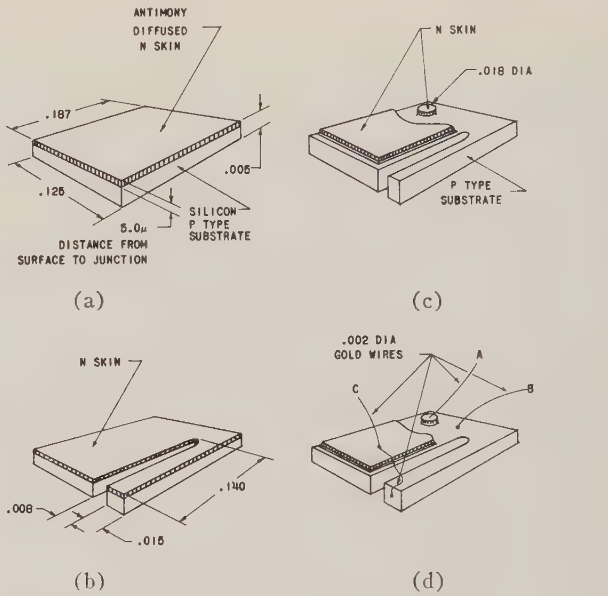


Fig. 2—Detailed sketch of a silicon integrated microcircuit.



(a) (c)

(b) (d)

Fig. 3—Fabrication phases of a microcircuit. (a) Diffused slab, (b) resistive channel formed after chemical etch, (c) diode and capacitive regions isolated after chemical etch, and (d) contacts made to appropriate surface locations.

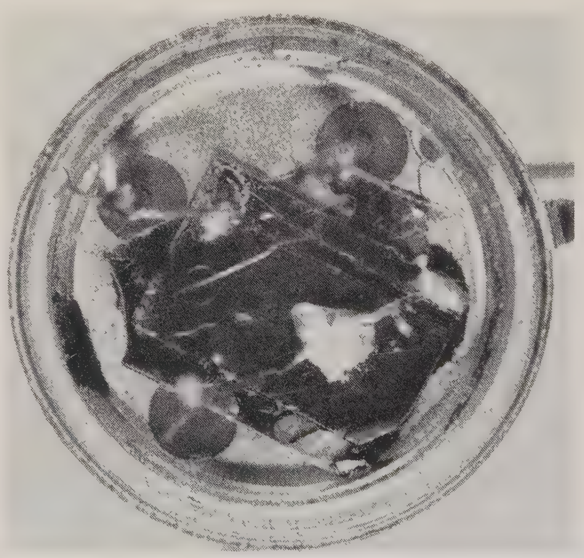


Fig. 4—Photomicrograph showing completed silicon integrated microcircuit mounted on a JETEC-30 type transistor stem.

B. External Structure Design

Factors concerning desired electrical performance and technology limitations determine the final external structure pattern. In operating effectively as an AM demodulator, a microcircuit exhibits a storage decay feature which is related to the modulating frequency in a certain manner.[5]

A relationship between storage decay and modulating frequency is given by the following expression:

$$\frac{1}{\tau} = \frac{1}{RC} > \frac{\omega_m m}{\sqrt{1 - m^2}}. \qquad (1)$$

Where R is the dissipative resistance, C is the storage capacitance, ω_m is the modulating frequency, and m is the degree of modulation. The expression stated in (1) is based upon the requirement that signal voltage decays must be followed exactly by storage section voltage decays. To suit the demands for voice signal demodulation, a time constant was sought such that $50 < RC < 600$ microseconds.

In addition to this electrical requirement, the final structure pattern had to conform to limitations of technology. A minimum slot width attainable by using a chemical etch technique presents a design limitation. The remaining technology factor to be considered in determining the external structure pattern surrounds the brittle mechanical nature of silicon. To gain appreciable storage time constant magnitude, a resistive region of small cross-sectional area is desirable. However, a limit is reached where breakage is a serious problem. Breakage occurs when attempts are made to mount structures on pedestals and during the final step of making electrical ohmic contacts. Actually, the breakage factor also determines the maximum slot length attainable. Large slot length magnitude, of course, is desirable for attaining relatively large storage time constant magnitude. Summarizing, the horseshoe shaped external structure pattern selected yields an approximate storage decay time constant in accordance with the following:

$$RC = \rho \frac{l_R}{W_R \cdot t_R} \cdot \phi(v) l_R (W - W_S - W_R) \qquad (2)$$

where ρ is resistivity, l_R is length of resistive channel, W_R is width of resistive channel, t_R is thickness of resistive channel, W is slab width, W_S is slot width, and $\phi(v)$ is a function describing per unit area junction transition capacitance variation as a result of applied voltage changes. To obtain large time constants, l_R should be maximized and W_R, t_R, and W_S minimized.

C. Internal Structure Design

The internal structure pattern is determined by factors related to electrical performance requirements. The type of diffused junction which resulted from fabrication of the silicon integrated structure yielded a capacitance variation as a function of voltage, as described by the data contained in Fig. 5. Per unit area capacitance is found by relating values of capacitance shown to junction area. Since capacitance magnitude is sensitive to voltage and internal geometry,[6] it becomes necessary, in order to attain large time constant magnitudes, to use abrupt p-n junctions or limit operation to low voltages. From (2), substrate resistivity to achieve large time constant values should be as large as possible. The abrupt junction requires that low resistivity silicon substrate be used. Obviously, a compromise in resistivity was necessary, and, for the structure devised, a resistivity of 50-ohm centimeter was selected.

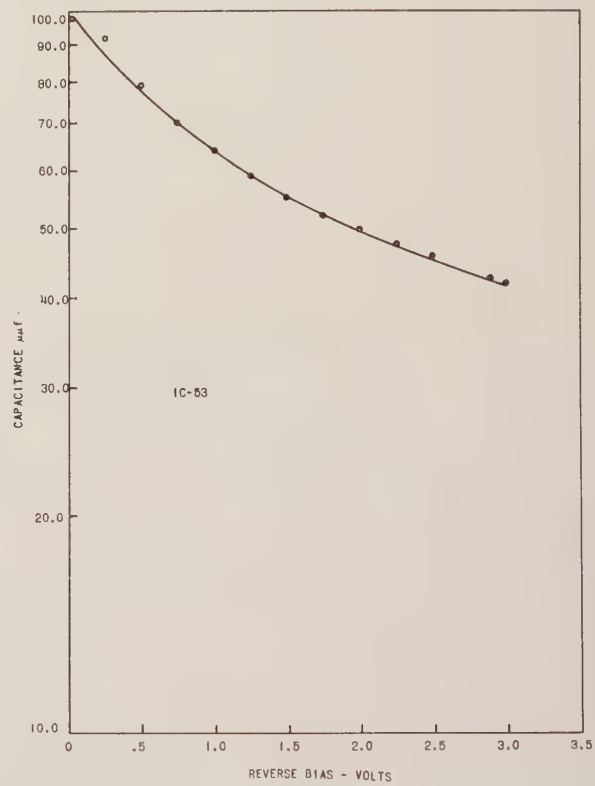


Fig. 5—Junction ac transition capacitance variation as a function of voltage. (Junction area is 0.02 square centimeter.)

From (2) and the curve of Fig. 5, the instantaneous time constant magnitude expected with an applied voltage of 1.0 volt is

$$\tau(v = 1.0 \text{ volt}) = 12.0 \text{ microseconds}.$$

To electrically examine the energy storage characteristic of the demodulator microcircuit, pulse measurements were made. An electrical pulse of fast rise and decay was applied to terminal A of the demodulator in such a direction that the diode was forward biased. Terminal C was common to both input and output. Terminal B was the output terminal electrically connected to an oscilloscope through a decoupling cathode

[5] S. Seeley, "Electron Tube Circuits," McGraw-Hill Book, Co., Inc., New York, N. Y., pp. 350–352; 1950.

[6] L. J. Giacoletto, "Junction capacitance and related characteristics using graded impurity semiconductors," IRE Trans. on Electron Devices, vol. ED-4, pp. 207–215; July, 1957.

follower. A schematic diagram of the arrangement is shown in Fig. 6.

The curves illustrated in Fig. 7 describe the pertinent waveforms in the examination of a typical integrated microcircuit demodulator. Since demodulation is usually performed at comparatively low signal voltages, the pulse input voltage amplitude was maintained at 2.8 volts during the electrical examination. Assuming that the storage decay occurs in an exponential manner in which the time constant is fixed, a value for the magnitude of τ is obtained which is approximately 14.0 microseconds. A conventional diode, fixed resistance, and fixed capacitance were assembled into a circuit, as

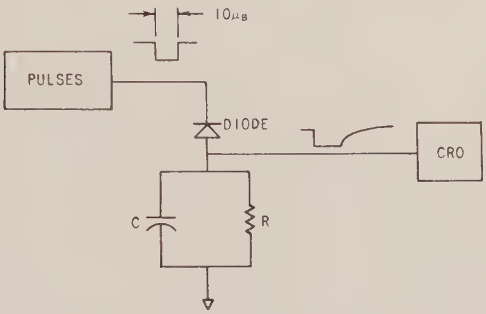


Fig. 6—Schematic illustrating arrangement of apparatus used in pulse measurements.

shown in Fig. 1, and examined in the same way as the integrated circuit. The waveforms obtained in examining the conventional circuit are shown in Fig. 8.

With the conventional circuit, there is no indication of a partial instantaneous voltage decay occurring at the moment of applied pulse decay. From the decay waveshape, the time constant is deduced to be approximately 9.0 microseconds. From the values of the fixed resistance and capacitance used (33,000 ohms and 270 $\mu\mu$f), the computed time constant is found to be $\tau = RC = 8.9$ microseconds.

The instantaneous partial voltage decay can be explained in terms of the detailed circuit representation of the microcircuit shown in Fig. 9.

The storage decay pattern may be analyzed in terms of the lower portion of the circuit schematic between B and C. At the moment the switch is opened, the output voltage at B will decrease instantaneously because of the IR drop in $R_C f_1(T)$ of the capacitive branch. The resistance exists in the form of a distributed impedance between the silicon surface location of terminal B and the capacitor junction depletion layer.

As mentioned previously, various basic material and structure properties of a temperature-sensitive nature would affect the microcircuit operation under varying thermal conditions. The microcircuit was electrically examined under varying temperature conditions, using electrical pulse measuring technique. The integrated circuit was mounted unencapsulated in a darkened chamber through which filtered argon was moving. Heat was removed and added so as to cause temperatures to exist from $-75°$C to $+150°$C. Waveforms obtained during the temperature cycling period for a

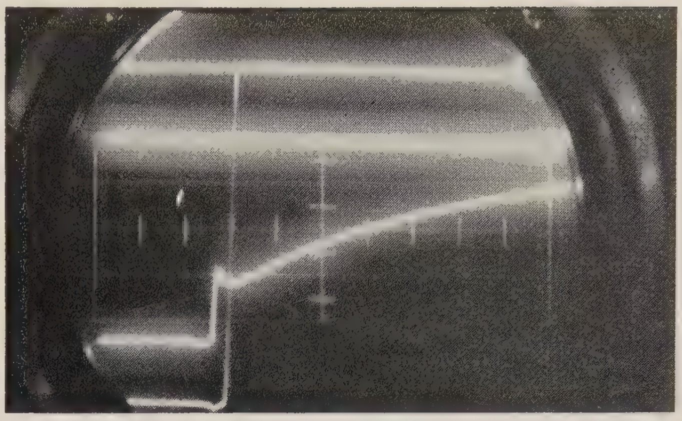


Fig. 7—Applied input voltage pulse and output pulse from the silicon microcircuit. (Horizontal = 2.0 μsec/cm. Vertical = 0.33 volt/cm.)

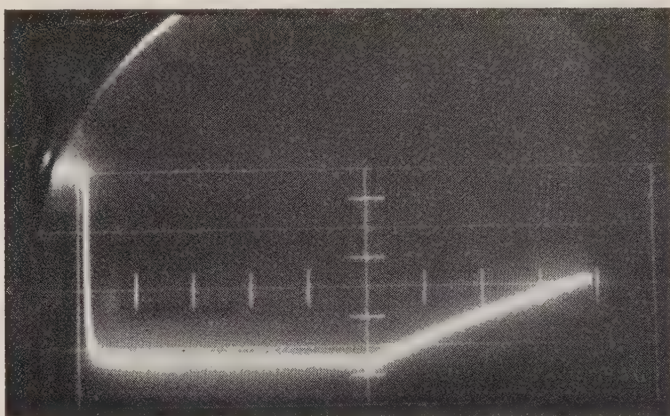


Fig. 8—Output waveform obtained from conventional demodulator when pulsed with a square wave. (Resistance value = 33 K ohms, capacitance value = 270 micromicrofarads, horizontal = 2.0 μsec/cm, and vertical = 0.33 volt/cm.)

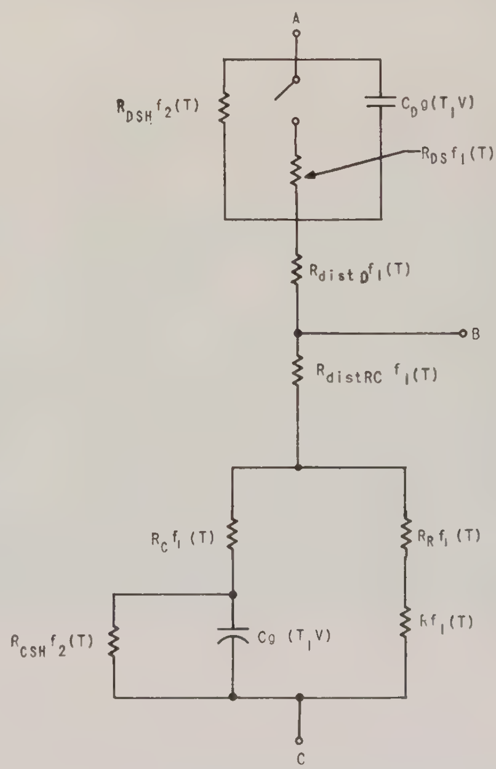
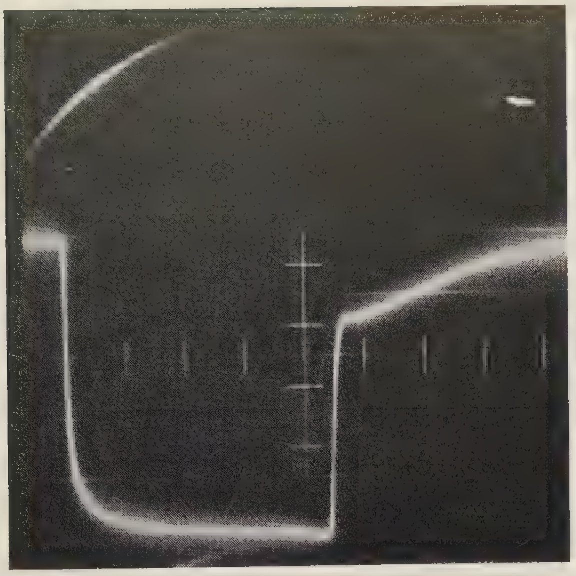
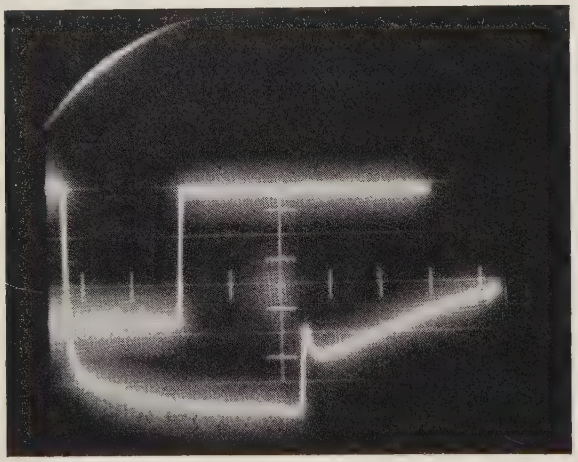


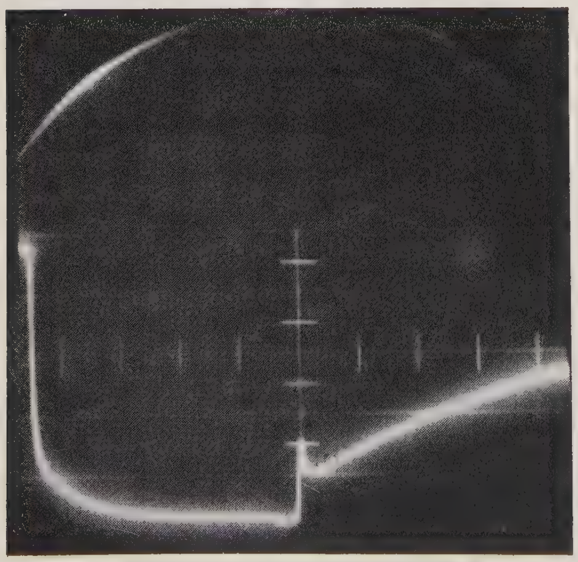
Fig. 9—Schematic diagram showing details of a simple microcircuit.



(a)



(b)



(c)

Fig. 10—Waveforms obtained in observing microcircuit response to temperature changes. (a) +150°C response, (b) 25°C response of microcircuit and input voltage pulse (vertical = 1.0 volt/cm), and (c) −65°C response (horizontal = 2.0 μsec/cm, vertical = 0.33 volt/cm, except as noted in (b)).

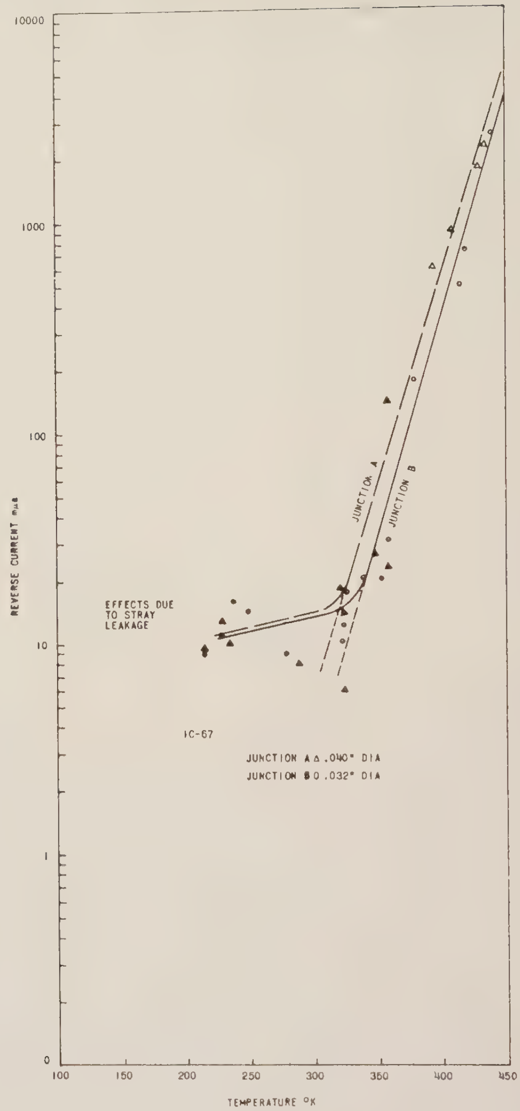


Fig. 11—Junction reverse current leakage vs temperature.

typical microcircuit are illustrated in Fig. 10. Analysis of the waveforms indicates that useful elevated temperature performance is limited by the junction reverse leakage current effects. Typical reverse current variation as a function of temperature changes is illustrated in Fig. 11. At 100°C the shunt leakage resistance value of a large area junction can be as small as 10,000 ohms, which severely affects the storage section of the circuit. In addition, the diode no longer opens as an ideal switch.

To further attempt to understand the microcircuit behavior, the temperature sensitivities of the substrate resistivity and junction capacitance were examined. A tiny bar of p-type substrate was subjected to varying heat conditions. Results of examination of the bar material properties are presented by the curve shown in Fig. 12. A positive temperature coefficient of resistivity is indicated. In examining a circular junction area for capacitance temperature sensitivity, the data illustrated in Fig. 13 were obtained. At low bias voltage levels, capacitance was found to vary directly with tem-

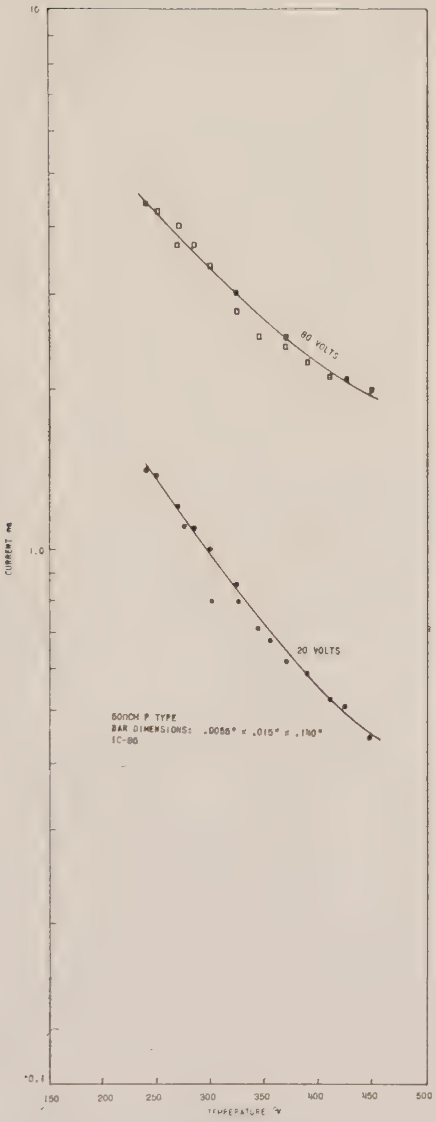


Fig. 12—Conduction through silicon bar sample as a function of temperature.

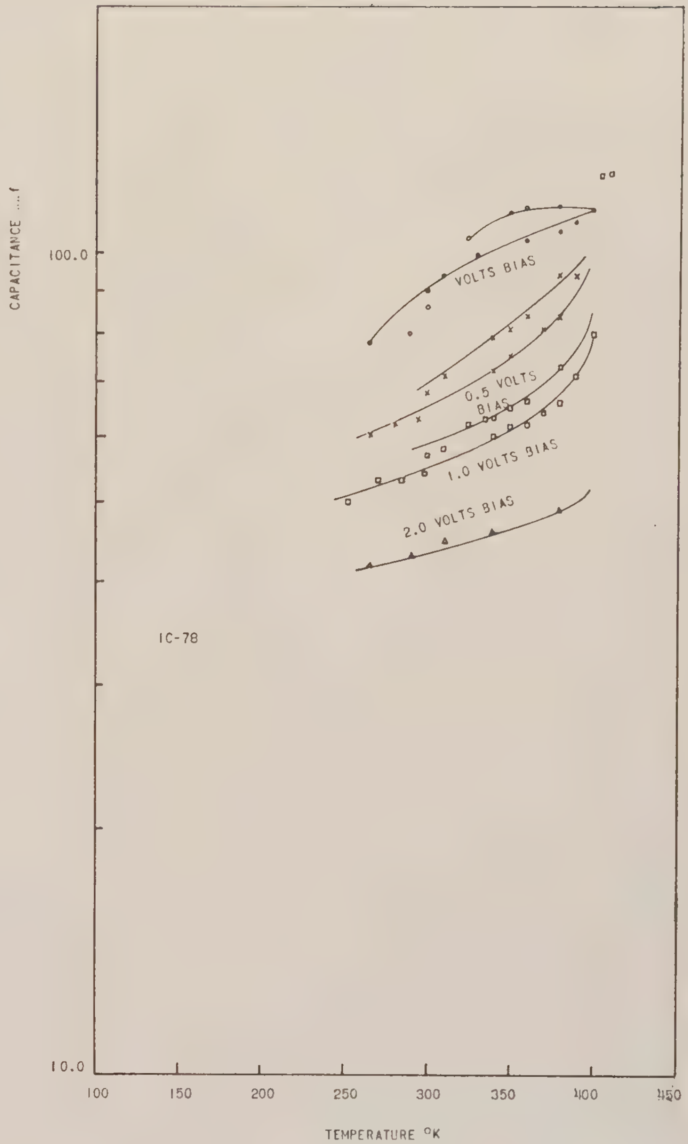


Fig. 13—Capacitance of a diffused junction as a function of temperature.

perature magnitude. Leakage current effects are responsible for the apparent tremendous variation of capacitance in the high temperature region. The combined temperature effects of resistivity and capacitance are such as to give a net positive temperature coefficient of storage time constant τ.

As mentioned previously, the time constant magnitude is related to resistance and capacitance magnitudes as,

$$\tau = RC.$$

Hence,

$$\frac{d\tau}{dT} = \frac{RdC}{dT} + \frac{CdR}{dT}. \tag{3}$$

Assuming linear capacitance and resistivity variations with temperature such as

$$R(T) = R_0[1 + \alpha_r(T - T_0)], \tag{4}$$

and assuming a constant voltage reference

$$C(T) = C_0[1 + \alpha_c(T - T_0)], \tag{5}$$

then

$$\frac{d\tau}{dT} = RC_0\alpha_c + CR_0\alpha_r. \tag{6}$$

In terms of percentage change per degree of temperature change,

$$\frac{\frac{d\tau}{dT}}{\tau} 100\% = \frac{C_0\alpha_c}{C} + \frac{R_c\alpha_r}{R} 100. \tag{7}$$

At the reference R_0, C_0

$$\frac{\frac{d\tau}{dT}}{\tau} 100 = (\alpha_c + \alpha_r)100.$$

From data derived from the curves in Figs. 12 and 13 and a room temperature reference,

$$100\ (\alpha_c + \alpha_r) = 1.25 \text{ per cent.}$$

The analysis indicates that large changes in the mechanism governing time constant occur for the type of temperature changes that would be expected in a typical operation. Fig. 9 shows that storage capacitance varies as a function of temperature. Diode capacitance is indicated as behaving similarly to storage capacitance.

The data presented in Fig. 10 indicate that large time constant changes did not occur under increasing temperature conditions. In the high temperature region this may be explained in part by shunt leakage across the storage capacitance. Actually, a simple energy dissipation system does not exist in the silicon structure as originally assumed.

Fig. 9 illustrates that capacitive storage decay can occur through two possible paths which form a parallel shunt impedance. Again,

$$\tau = R_\Sigma(T)C(T),$$

but

$$R_\Sigma(T) = \frac{R_{csh}(T) \cdot R_s(T)}{R_{csh}(T) + R_s(T)}, \tag{8}$$

where R_{csh} (T) is temperature dependent junction shunt leakage resistance, $R_s(T)$ is total series bulk resistance, including distributed effects, and $R_\Sigma(T)$ is the total shunt resistance as a function of temperature. Also

$$R_{csh}(T) = R_{co}e^{.07(T_o - T)}, \tag{9}$$

where R_{co} is a reference shunt resistance (one to five megohms) at room temperature, T_o is reference temperature, and T is the variable temperature.

In addition,

$$R_s(T) = R_{so}[1 + \alpha_r(T - T_o)], \tag{10}$$

where R_{so} is a reference series bulk resistance including distributed effect, T_o is a reference temperature, T is the variable temperature and α_r is the temperature coefficient of resistivity.

The total shunt resistance is then

$$R_\Sigma(T) = \frac{R_{co}e^{.07(T_o - T)} \cdot R_{so}[1 + \alpha_r(T - T_o)]}{R_{co}e^{.07(T_o - T)} + R_{so}[1 + \alpha_r(T - T_o)]}. \tag{11}$$

The percentage change in time constant magnitude per degree change of temperature now is,

$$\frac{\frac{d\tau}{dT}}{\tau} 100 = \frac{C(T)dR_\Sigma(T) + R_\Sigma(T)dC(T)}{R_\Sigma(T)C(T)} 100 \tag{12}$$

$$= \left[\frac{dR_\Sigma(T)}{R_\Sigma(T)} + \frac{dC(T)}{C(T)}\right] 100.$$

If $R_{co} = mR_{so}$, then (11) can be simplified to

$$R_\Sigma(T) = R_{so}\frac{me^{.07(T_o - T)} \cdot [1 + \alpha_r(T - T_o)]}{me^{.07(T_o - T)} + [1 + \alpha_r(T - T_o)]}. \tag{13}$$

From the experimental results, $m = 40$.

The function $R_\Sigma(T)$ is plotted in Fig. 14. The data in Fig. 14 indicates that storage capacitance leakage current effects substantially influence storage time constant in the region of operation above room temperature.

Diode capacitance and shunt leakage effects also influence the storage time constant feature of the microcircuit. These act in such a way as to tend to decrease the storage factor as a response to increasing temperatures. In Fig. 14, calculated time constant values $\tau = R_\Sigma(T)C(T)$ are plotted as a function of temperature. This plot excludes diode effects.

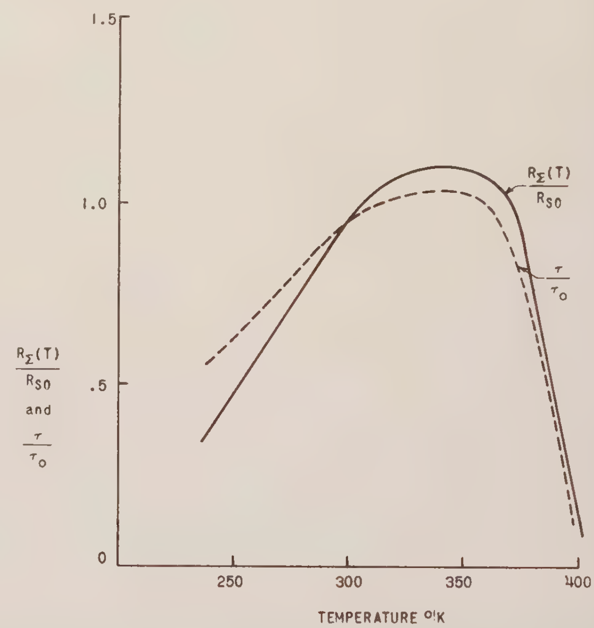


Fig. 14—Plot showing calculated shunt resistive dissipation change and time constant change as a function of temperature.

Fig. 15 illustrates the relationship of storage capacitance and dissipative resistance in determining time constants. Time constant values attained in performing experimental work and using the pure silicon integrated circuit approach are indicated in the sketch. Various deviations from the pure silicon integrated microcircuit approach enable slab structures which exhibit a wide range of storage ability to be fabricated. Various deviations indicated in Fig. 15 refer to silicon structure equal in size to those structures which have been described. Fig. 16 (p. 467) describes a proposed four-layer silicon structure pattern designed to operate with large storage time constant. The abrupt p-n junction yields very large per unit area capacitance, and the thin high resistivity layer contributes large bulk resistance, where needed.

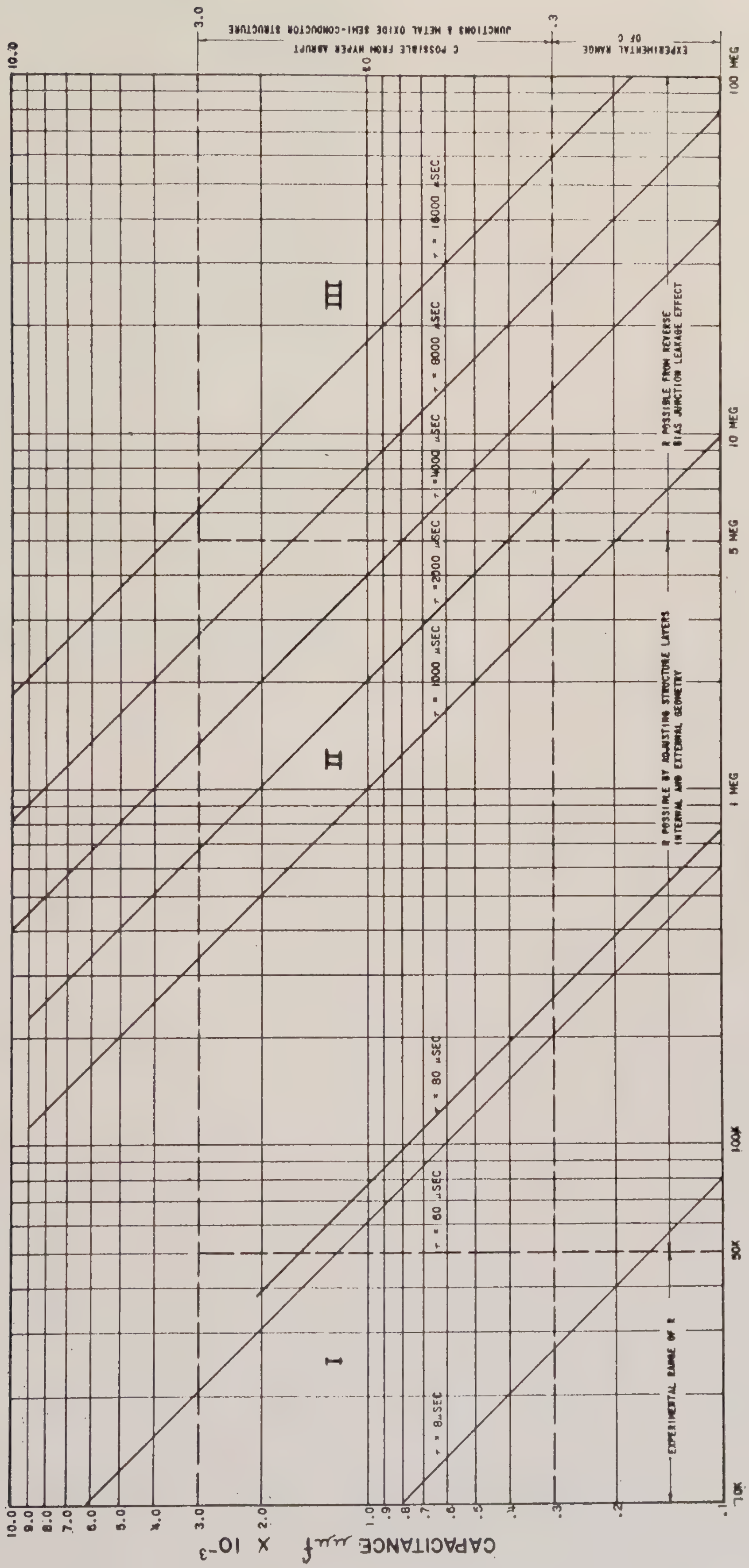


Fig. 15—Plot showing achievable time constant regions as a function of the type of resistive and capacitive structure used. (Useful AM demodulator time constants for audio use indicated.)

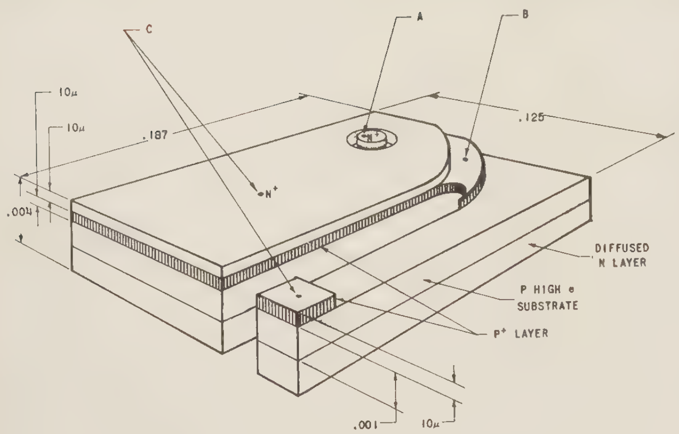


Fig. 16—Silicon structure that will permit improved electrical microcircuit performance as a demodulator.

Internal electrical connections are made through the p^+ channel which reduces unwanted distributed resistances. Ohmic electrical connections are made to locations B and C through a heavily doped p^+ region.

In addition to microcircuit examinations using pulse techniques, various integrated units were examined while performing the role of AM demodulation. Curves in the photograph presented in Fig. 17 illustrate the demodulator action of a typical microcircuit.

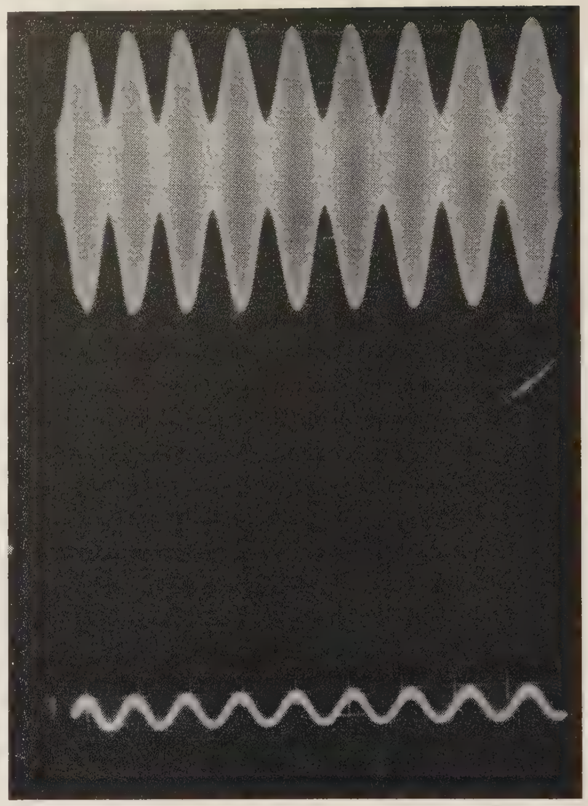


Fig. 17—Modulated carrier input to microcircuit demodulator and output waveform for carrier frequency of 1.5 Mc, $m=90$ per cent, and $\omega_m=1000$. (Vertical = 0.33 volt/cm. Horizontal = 900 μsec/cm.)

Summary and Conclusions

A circuit illustrating a type of one-for-one replacement approach to micromicrominiaturization has been described. Identification has been made of characteristic features of pure semiconductor integrated microcircuitry. A silicon integrated microcircuit structure has been designed and constructed in such a way as to become a slab capable of performing a simple electrical circuit function. Pulse measurements indicate that the silicon structure produced possessed switching and storage effects essential for operation as a simple AM demodulator. Observations were made of responses of the microcircuit to variations of environmental heat conditions. Appreciable time constant changes did not occur throughout a large temperature range. The use of distributed resistances was found to introduce desirable and undesirable effects in electrical circuit performance. Analysis of the structure demonstrated that thermal behavior of the microcircuit operation depends upon temperature sensitive surfaces and bulk properties. Experimental microcircuits were operated successfully as AM demodulators.

The pure semiconductor integrated microcircuit approach to miniaturization is worthy of further investigation. Careful analyses of the interdependencies of basic semiconductor material properties, surface effects, technology factors, and electrical performance requirements, including temperature factors, are necessary in determining slab-structure patterns. An active microcircuit, including an amplifying element, will introduce additional design factors of minority carrier lifetime and surface recombination effects not considered in the experimental work described.

Deviations from the pure integrated approach outlined will introduce desirable and undesirable effects. Guided by the many controlling design factors, slab-structure patterns can be devised, which will perform electrically with an acceptable amount of temperature stability over wide temperature ranges. The final semiconductor surface form of the circuit will be a key determining factor of electrical environmental performance. Diode and transistor device history has been involved with surface problems which certainly will continue to be present in microcircuit activity. Surface leakage effects seriously limit the useful elevated temperature range of the pure integrated circuit.

Where stability of circuit parameters is essential, careful designing will be necessary to extend the pure slab circuit operating temperature range above 90°C.

Use of distributed resistances for internal bulk connections will be objectionable in many circuit designs.

Acknowledgment

The author wishes to thank A. P. LaRocque and R. S. Yatsko for the preparation of diffused surface layers, W. Pharo for silicon material preparation, A. Mark in the design of a special heat-control chamber, and W. Cherry for his helpful discussions.

Functional Circuits Through Acoustic Devices*

E. GIKOW†, MEMBER, IRE, A. RAND†, AND J. GIANNOTTO†

Summary—In essence, the communication specialist in the field with his complex electronic gear and the native who beats a hollow log both perform the same function—communication over a distance. However, there is no gainsaying that the hollow log is undoubtedly the more reliable of the two communication equipments.

The implication of this analogy is not as far fetched as it may appear. It has been found that considerable circuit simplification with a consequent increased reliability are attainable through the application to electronic circuits of the mechanical and acoustic properties of certain materials. Miniaturized, rugged, low cost, highly selective band-pass filters ranging from 100 cps to approximately 10 Mc are feasible. Power transformers without core or coil are definite possibilities. Stable delay media provide large delays in small simple packages. Hybrid structures of conventional parts and nonconventional resonators provide techniques for broadbanding and impedance transformation. A new element, it is expected, will soon be generated for use at low frequencies—a passive four-terminal nonreciprocal network.

Introduction

With the Army's concern with portability, miniaturization has been an important goal. The pressure has been for ever smaller and lighter electronic parts. However, the component engineers have long been aware of the inherent size and performance limitations of conventional parts. This is particularly true of inductive parts. If the inductance is held constant, the smaller the inductor, the finer the wire size. The result is an increase in the resistance of the conductor with a consequent degradation in performance.

Miniaturization is not the only problem. Tactical demands call for increased use and, unfortunately, increasingly complex electronic systems. As a consequence, performance demands placed on the electronic parts have become more stringent. Finally, the mere increase of parts in equipment imposes a reliability burden of considerable magnitude, in that simple statistics dictates that each part must have an improved reliability if the over-all operating reliability is to be maintained at a reasonable level. As a result of the above problem, there has been a continuing search for less conventional approaches to circumvent these barriers.

What are needed are simple devices or materials which perform complex functions to resolve this irreducible minimum of size and parts that conventional methods foretold. It is this thought that has led us into placing increasing effort in a somewhat anomalous field for the electronic engineer.

It has been found that improved performance, considerable circuit simplification, with a consequent increased reliability, are attainable through the application to electronic circuits of the mechanical and acoustic properties of certain materials. Much has already been accomplished and more is projected by exploiting the ramifications of such phenomena as ferroelectricity of ceramics, magnetostriction of ferrites, stable high Qs of mechanical resonators, and the low velocity of propagation of sound in solids. Through electromechanical conversion, it is possible to perform relatively complex circuit functions by means of simple geometric structures.

As opposed to the usual concern with current, voltage, inductance, capacitance, and resistance, we are concerned with the analogous mechanical characteristics: velocity, force, mass, compliance and friction. Low velocity of propagation gives us miniaturization and reliability in delay lines. Relatively high electromechanical coupling coefficients in ceramic resonators provide broad-band filter capabilities at a low cost in small sizes and simple structures. The high mechanical Q and stable nature of certain nickel alloys permit the design of narrow-band precise filters not attainable with conventional LC networks. Fortunately, the actual design work is best carried on by treatment of the electrical equivalent of the mechanical systems. These electrical equivalents dramatically illustrate the circuit simplifications attainable by these functional approaches.

Surprisingly, there is considerable latitude in the design of mechanical resonant elements where engineering judgment may be employed for optimum results. Thus, the choice of the mode of propagation is made by balancing physical size, cost of fabrication, spurious response, loss per unit volume, voltage gradient, etc.

What follows is a discussion of the various devices which have been worked on, are currently being developed, and areas of planned future effort. Because of the scope of this field, discussion on each particular device is considerably limited. However, an attempt has been made to provide as extensive a bibliography as possible for those interested in greater details.

Electromechanical Filters

In the interest of spectrum conservation, particularly with the advent of single sideband communications, filtering requirements have become more and more stringent and the shortcomings of conventional electrical elements have become a limiting factor in filter designs. The losses and instability of electrical resonant elements have placed a lower limit on the fractional bandwidth of intermediate frequency electrical filters. The inherent properties of solid elastic materials, used as mechanical resonators, and the development of metal

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alloys with the features of low loss, high Q and stable temperature characteristics, has added impetus to the development of electromechanical filters.

Regardless of the mode of vibration, all electromechanical filters operate basically in the same manner. The filter is a mechanically resonant device which receives electrical energy at the input circuit, converts it into mechanical vibration, then converts the mechanical vibration back into electrical energy at the output.

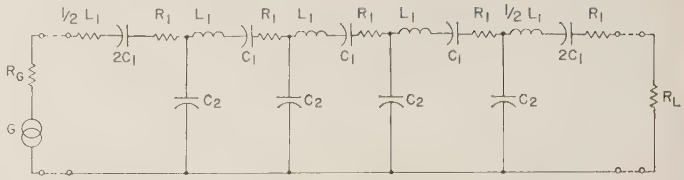
Analysis of a rapidly vibrating mechanical system is much more complicated than the similar analysis of an electrical circuit. For symmetrical mechanical systems, analogous electrical circuits are used to facilitate designing of mechanical filters and predicting their behavior. From a functional viewpoint, an electromechanical filter consisting of half wavelength resonant elements coupled by elements of one quarter wavelength can be represented by the equivalent electrical circuit shown in Fig. 1(a). This is illustrative of the reduction in parts such filtering techniques provide.

A large number of filter structures have been designed, some successful, others impractical. Of the many possible designs, three types of resonant elements are the most common and have proven successful in use in military and commercial equipments. One employs a ladder-type structure with resonant plates interconnected by fine wires. Another utilizes a cylindrical rod machined to produce alternate necks and slugs. The third type of filter uses a cylindrical arrangement with disk resonators interconnected by coupling wires. Each type will be treated in further detail.

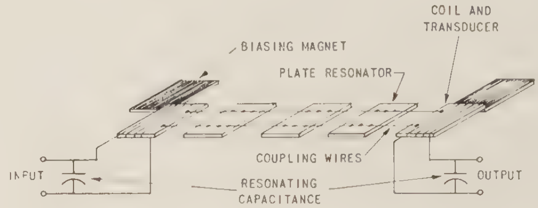
Plate Type Structure

A practical design for a plate-type mechanical filter was presented in articles by Adler [1] and Lapin [2]. The filter structure consists of a series of resonant, thin, rectangular, metal plates, vibrating in an extensional mode, with motion parallel to the long axis of the filter. The two thin wires interconnecting each pair of plates expand and contract to provide elastic coupling [Fig. 1(b)].

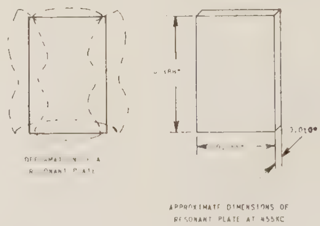
The bandwidth may be changed by three basic means: 1) varying the diameter of the coupling wires; 2) varying the thickness of the resonant plates; 3) selecting the point of connection of the plate, for example, where the amplitude of vibration on the plate is a maximum and the impedance is lowest. With the coupling wires attached to a location of lower amplitude of vibration, a higher impedance point is utilized and has the effect of decreasing the bandwidth. From a practical standpoint, the bandwidth of a plate-type structure is limited by the introduction of spurious response when plate thickness is increased radically, and by weakness in the structure caused by the reduction in coupling wire diameter. Inasmuch as the resonant plates are fabricated of materials having mechanical Qs of the order of 10,000, bandwidths as small as 500 cps at a center frequency of 455 kc are attainable.



(a)



(b)



(c)

Fig. 1—(a) Electrical analog of a five-plate mechanical filter. (b) Filter structure with plate-type resonators. (c) Relative deformation of a vibrating resonant plate.

For a given material the center frequency of this type of filter is determined by the length of the plates. The resonant plates at 455 kc have dimensions in the order of 0.225 inch long by 0.388 inch wide by 0.010 inch thick and can be stamped out to an accuracy of 50 cycles. Because of the low cost of the resonators, precision of center frequency is attained by selection rather than the more costly adjustment in the final assembly. Fig. 1(c) shows an exaggerated sketch of the relative deformation of a vibrating resonant plate.

The skirt selectivity, a measure of the rejection quality of the filter, is determined by the number of resonant plates used. However, beyond seven plates, the decrease in skirt ratio is slow and improvements are obtained at increasing cost and size. Table I illustrates this rate of improvement of skirt selectivity by increasing the number of resonators.

TABLE I

No. of Resonators	Approx. Skirt Selectivity (BW 60 db/BW 6 db)
7	1.8
9	1.5
11	1.3
17	1.1

Neck and Slug Structure

This type of structure has been discussed in detail in articles by Roberts, Burns, George, and Lundgren [3–5]. Fig. 2(a) shows a neck-coupled configuration, operating in the torsional mode. The large diameter resonators or slugs act as tuned circuits which are connected by small diameter necks which act as couplers. As in the plate type, this structure acts as a chain of capacitively coupled resonant circuits in cascade. The resonators are one-half wavelength long and the couplers are one-quarter wavelength long. At resonance, one end of the cylindrical resonator vibrates in rotation about the axis; this is opposite to the direction of motion of the other end. The ratio of coupler to resonator diameters determines the bandwidth of the filter.

The resonators of a torsional mode structure are individually tuned by clamping adjacent resonators. The frequency of the resonator under test is measured by coupling energy into the coil of an external measuring circuit. For incremental adjustments, the center frequency can be lowered by removing material from the middle of the resonator, or increased by removing material from the ends. The velocity of sound in the torsional filter is approximately 35 per cent less than in the longitudinal type; therefore, a filter designed to operate in the torsional mode is approximately 35 per cent shorter in length than its longitudinal counterpart. At a center frequency of 455 kc the approximate dimensions of the resonant element are 0.124 inch long by 0.180 inch in diameter. The entire resonant structure, less the transducers, is precision machined from one piece of nickel alloy.

Disk Structure

The third type of filter, shown in Fig. 2(b), employs a series of resonant metal disks, coupled by wires welded to their peripheries. Articles by Doelz, Hathaway, and Brown [6], [7] discuss this electromechanical filter typein detail. The disk resonators are designed to vibrate with motion perpendicular to the flat surface. This flexure type resonator has been designed to vibrate in either of two basic nodal patterns.

In most instances in designs for filters below 200 kc, the pattern with one circle or fundamental mode is employed [see Fig. 2(c)]. Between 200 and 600 kc, the first overtone or two nodal circle pattern is usually employed. The particular mode is selected to obtain the most convenient disk size and minimum spurious response. Coupling between disks is provided by wires welded to the peripheries of the disk resonators. For given resonators, bandwidth varies as the cross-sectional area of the coupling wires. The resonant frequency is established by the thickness and diameter of each disk. Skirt ratio is determined by the number of resonators as in the previous filters discussed.

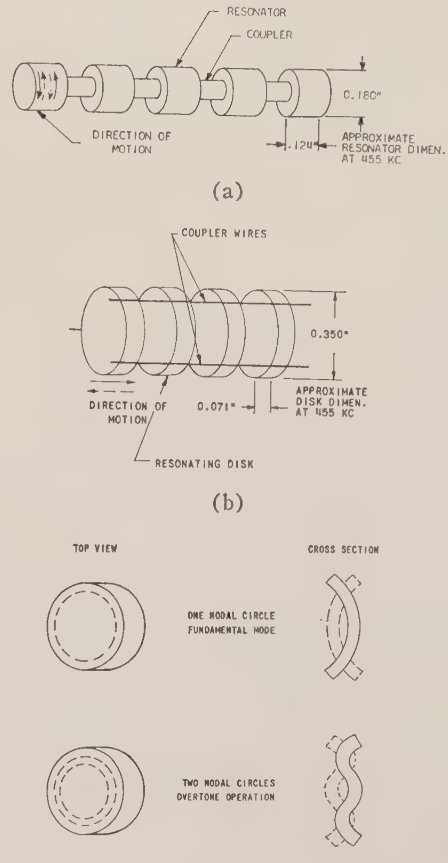


Fig. 2—(a) Neck and slug structure. (b) Disk structure. (c) Relative flexure of resonating disk.

Disk resonators are cut from rods of nickel alloy, then ground and lapped to critical precalculated dimensions. The disks are heat treated to relieve strains after grinding. Final tuning is accomplished by grinding a small amount of material from the flat surfaces.

Transducers

Transducers perform a double function. They terminate the filter with the correct impedance and provide electromechanical conversion. Magnetostrictive transducers have been employed almost exclusively because of their efficiency, economy and temperature stability. Nickel alloys and recently ferrites are the most widely used materials in magnetostrictive transducers. A magnetic biasing field is required to optimize coupling and prevent frequency doubling. A permanent magnet is used to supply this bias. Figs. 3(a)–3(d) illustrate the various transducers used in the filter types discussed.

The principal advantages of metal transducers are their ruggedness, ease of fabrication, and good temperature characteristics. The major disadvantage is the high eddy current loss because of the relative thickness and low resistivity of the metal. This loss, which accounts for most of the insertion loss of the filter, is divided equally at the input and output transducer.

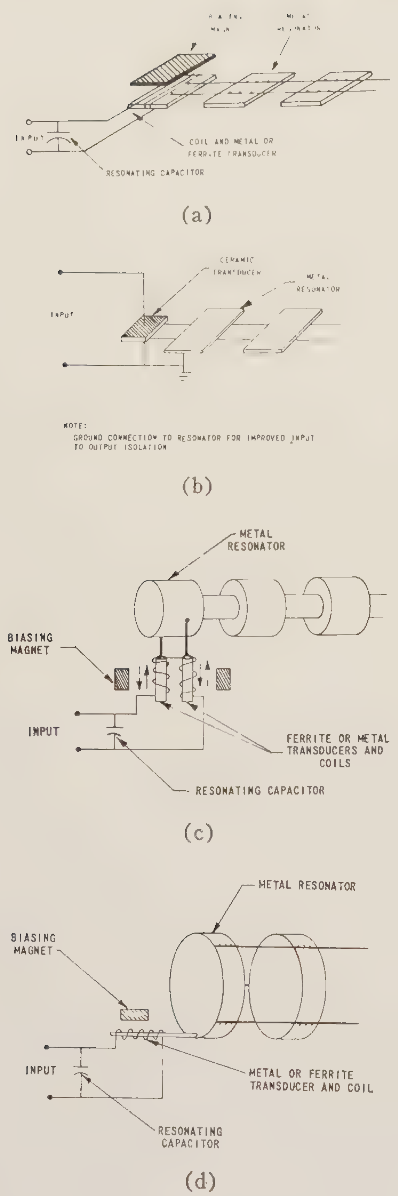


Fig. 3—(a) Metal or ferrite transducer with plate structure. (b) Piezoelectric transducer with plate structure. (c) Ferrite or metal transducer with slug structure. (d) Ferrite or metal transducer with disk structure.

Recently, magnetostrictive ferrites have been gaining favor as a transducer material. This is primarily attributed to its low eddy current loss, high coupling coefficient, and improved temperature stability of resonant frequency. The input and output impedance of a magnetostrictive filter are established by the coils surrounding the transducer and associated circuitry. Typical impedance values using only tapped coils range from 1000 to 50,000 ohms. However, additional circuitry can be used to obtain values outside this range.

Recent research and development effort on the plate-type filter have proved the feasibility and advantages of a piezoelectric drive. The principle of operation of this form of drive is treated in somewhat greater detail later in this paper. The use of this type of transducer results in a significant reduction in filter size and parts, since the coil, biasing magnet, and resonating capacitor are not needed. Other important advantages are the reduction of insertion loss, in that eddy current losses are eliminated. Also, since the metal resonators can be grounded, excellent front-to-back isolation results. Some mismatch between the transducer and resonator occurs at temperature extremes. This is evidenced by an increased pass band ripple. It is characteristic of such filters that low impedance is obtained using the ceramic transducers, approximately 30 to 150 ohms. However, external circuitry can be used to obtain the desired impedance.

General Performance

Performance characteristics of electromechanical filters involve the same considerations observed in the use of conventional electrical filters. The basic parameters pertinent to the use of mechanical filters are selectivity, pass band ripple, insertion loss, thermal stability, and setting of carrier or center frequency. However, there is one other consideration normally of small concern in *LC* filters, that is, spurious response. Just as unwanted resonances exist in conventional *LC* and *R* circuits, also in the mechanical system there are many simultaneous modes of vibration. Thus, a mechanical resonator designed for, say, longitudinal vibration may also exhibit modes of torsion, flexure, etc. The magnitude, proximity, and interaction of such other modes determines the spurious content.

Poor welds or solder connections on the resonators, bending action of a thin rod when vibrated longitudinally, dissymmetry in cross section of a resonator or coupler, inhomogeneity of materials, the improper mounting of the resonant structure are other causes of spurious responses. Quality control of material and special fabrication jigging has reduced or removed unwanted responses outside of the normal pass band to a level of 80 db down from the response at center frequency. Spurious responses of greater magnitude occur beyond 10 per cent of center frequency. Fig. 4 illustrates a typical spurious response of an electromechanical filter.

At the present state-of-the-art, the practical limits of frequency range are approximately 50 to 600 kc. One phase of effort under a Signal Corps contract [8], now underway, was directed toward the development of electromechanical filters at frequencies higher than 0.5 Mc. Investigations centered primarily in the 1.3-Mc region. Using fundamental mode and third overtone of 455-kc plates, results have proven rather unsuccessful because of the considerable spurious responses in the pass band (Fig. 5). Detailed information covering this high frequency investigation was made available in or about June, 1960.

A recent development in the plate-type filter, employing a motion reversal technique, has resulted in a skirt ratio of 1.1 to 1 [8]. This novel filter design utilizes 19 plates packaged in a total volume of less than 1 cubic inch. Motion reversal does not provide any improvement in performance. It is merely a technique employed

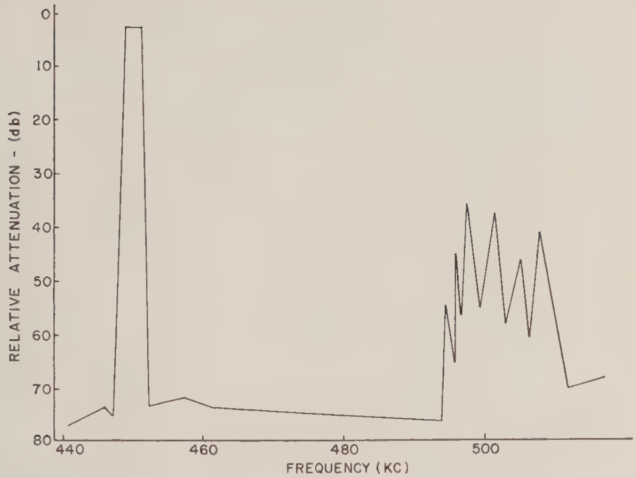


Fig. 4—Typical spurious response of an electromechanical filter.

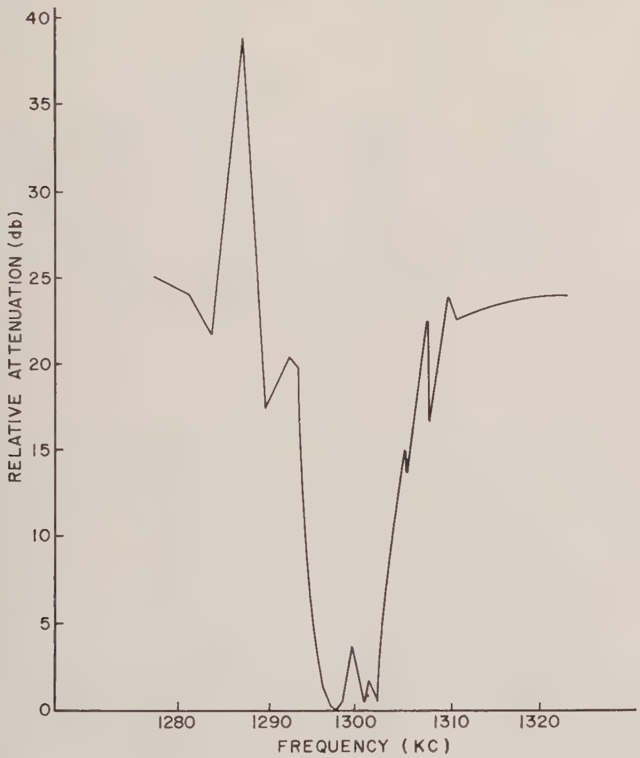


Fig. 5—Response of plate filter at approximately 1300-kc ferrite transducer.

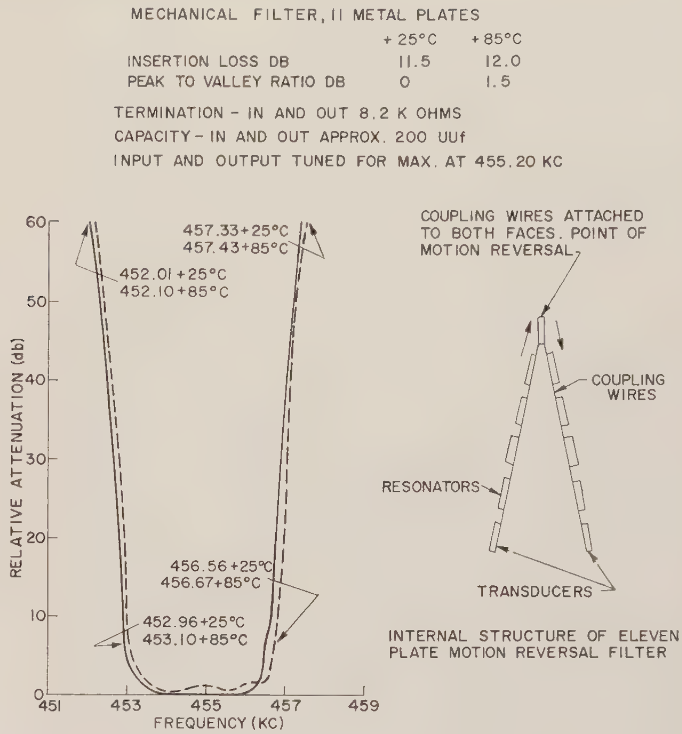


Fig. 6.

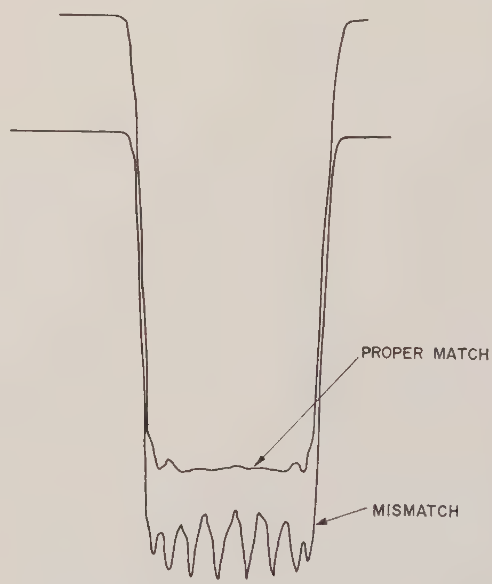


Fig. 7—Improvement of pass band ripple by proper reactive match.

to obtain a more convenient package. Fig. 6 shows how the motion reversal is obtained.

The ratio of maximum-to-minimum output level in the pass band is usually defined as the pass band ripple or peak-to-valley ratio. To produce electromechanical filter designs having a minimum pass band ripple, it is essential that the impedance match between the transducer and resonator be held to very close limits. Pass band ripple can be kept to a minimum by a proper match at the output and input of the filter. This involves the use of an external capacitor tuned to resonance with the driver coil. The improvement possible by such a match is shown in Fig. 7. Variations in pass band ripple, caused by a change in temperature, are normally of the order of 1 db.

Examples of Performance

Fig. 8 illustrates and tabulates the performance characteristics of a plate-type filter, using a metal magnetostrictive drive. This filter, developed under Signal Corps Contract No. DA36-039 sc-78156 [8], is intended for single sideband applications. Fig. 9 shows the response characteristics of a plate-type filter driven magnetostrictively using a ferrite transducer. Another plate-type variation, recently developed, uses a piezoelectric ceramic drive and metal center plates (Fig. 10). A compact, relatively low cost, five plate filter with a piezoelectric ceramic drive, was developed for use in portable

equipment where extreme selectivity is not essential (Fig. 11). Under Signal Corps Contract No. DA36-039 sc-78128 [9], a 455-kc torsional mode filter, using a magnetostrictive ferrite drive, was developed (Fig. 12). Fig. 13 shows the response of a flexural mode disk-type filter using a metal magnetostrictive drive.

Ferroelectric Ceramics

In the electromechanical filter the transducers provide electromechanical conversion and the resonant mechanical members are interconnected mechanically and provide the frequency selective transmission path. In the ferroelectric ceramic filter, the functions of transducer and mechanical resonator are not separate and distinct. These functions are integral within the individual resonant elements and it is therefore possible to electrically interconnect elements into π, T and ladder configurations as is done with conventional LCR elements, but with certain additional constraints. Standing wave stress patterns and electric-field intensity patterns make impedance transformation possible by selective electroding of ceramics.

Analogous to ferroelectric ceramic devices which use the phenomenon of electrostriction, are devices using the phenomenon of magnetostriction. Ferroelectric ceramics use prior electrostatic polarization. Magnetostrictive rods use the magnetic polarization of biasing magnets or dc currents.

When a thin pellet or strip of certain ceramics is properly fired in a kiln, and electroded on its opposite faces, a fixed capacitor is formed whose static capacitance is a function of its geometry and the dielectric constant of the material. Applying a polarizing voltage across the electrodes and maintaining this voltage while the temperature is reduced from the region of the Curie temperature of the material, a permanent electric polarization will result, which is, in a sense, similar to the magnetic polarization of a permanent magnet. As a result of the polarization forces, the randomly oriented dipoles are twisted and set into a preferred direction. At the same time the internal molecular binding forces are altered with a resultant change in dimensions. A body thus prepared may be called ferroelectric, by analogy with ferromagnetic, because a superimposed alternating electric field displays a similar "hysteresis" characteristic. The ceramics employed here have mechanical Q's ranging from 400 to 1400 and dielectric constants ranging from 400 to 1100.

Internal strains are set up in the materials in the course of polarization. The relief of these strains results in an aging process. As a resonant structure, there is a change with time of the resonant frequency because of this aging of the material. In earlier materials the effect of aging was quite severe, but with some of the newer ceramics the problem is considerably reduced. The change in resonant frequency is approximately linear with respect to the logarithm of time. In present ma-

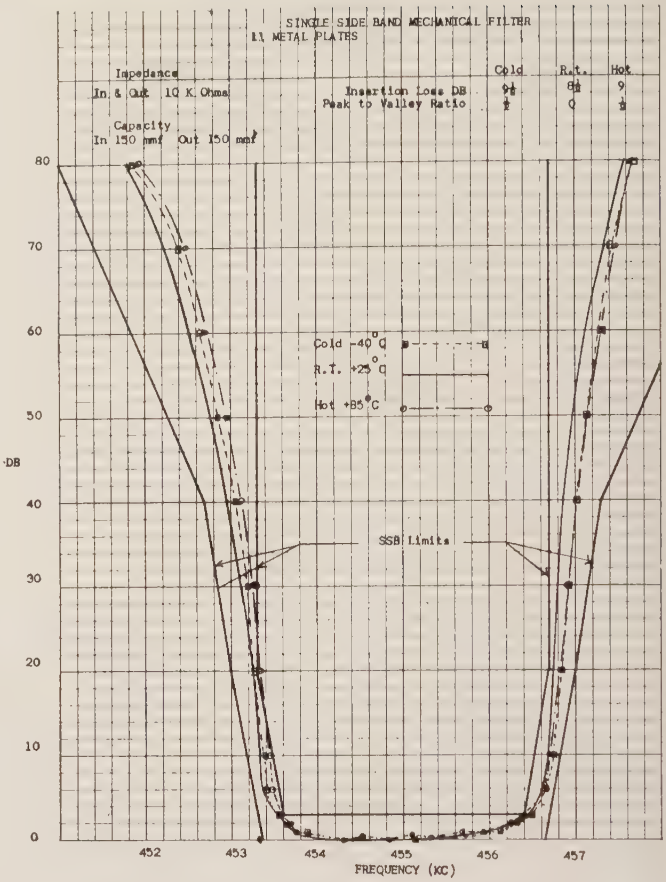


Fig. 8.

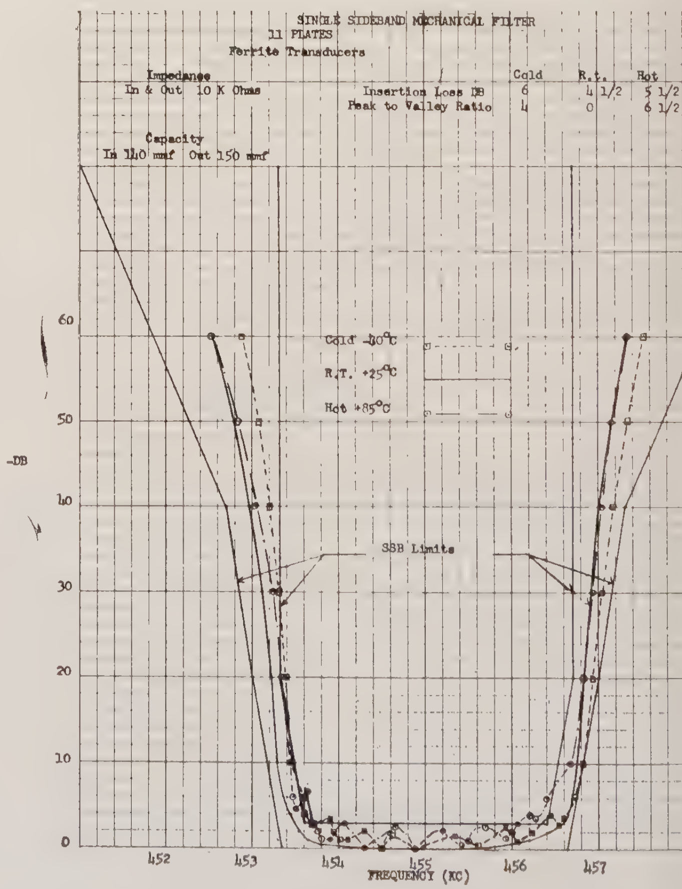


Fig. 9.

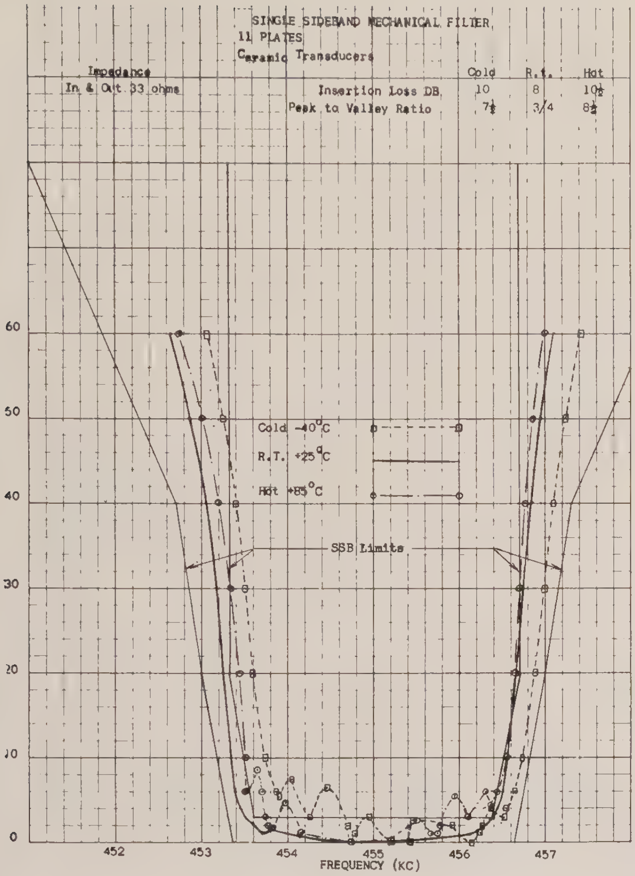


Fig. 10.

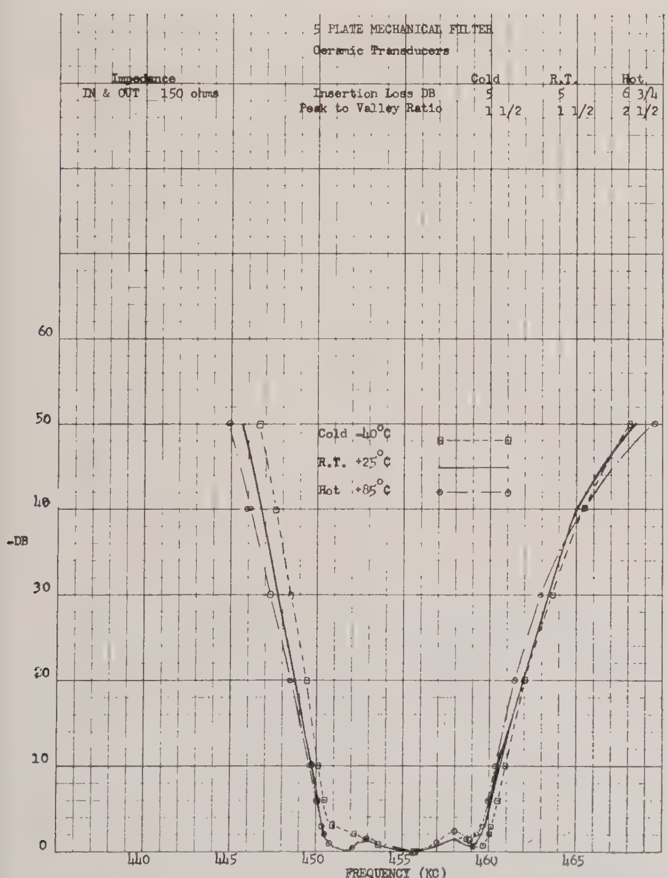


Fig. 11.

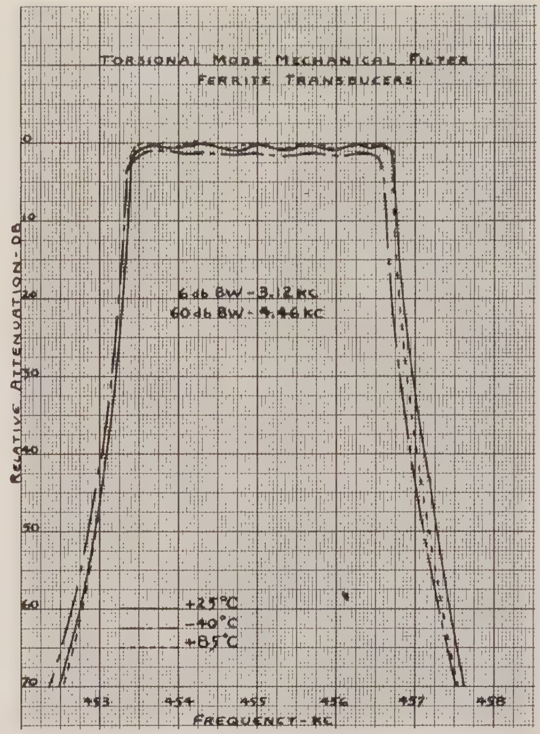


Fig. 12—Torsional mode mechanical filter—ferrite transducers.

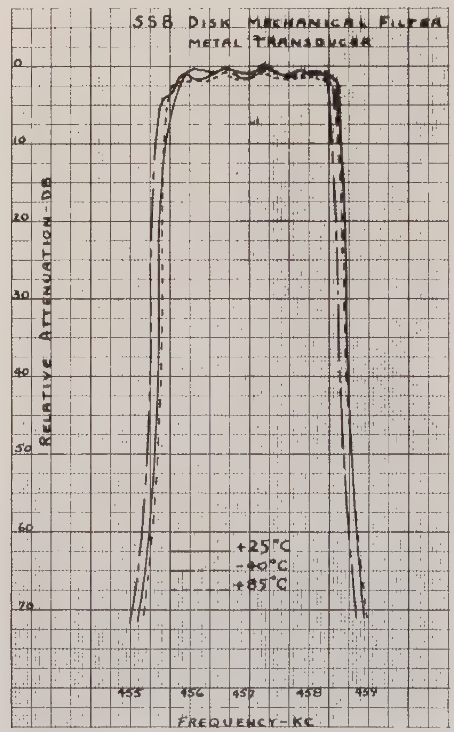


Fig. 13—SSB disk mechanical filter—metal transducer.

terials, the aging rate for radial-mode resonators is 0.06 per cent for a period of time which, measured in units of "time-since-polarization," is ten such units of time. For example, a 500-kc resonator polarized 60 days ago will drift approximately 300 cycles with the elapse of an additional 600 days. Acceleration of a preaging process is a subject of continuing materials research.

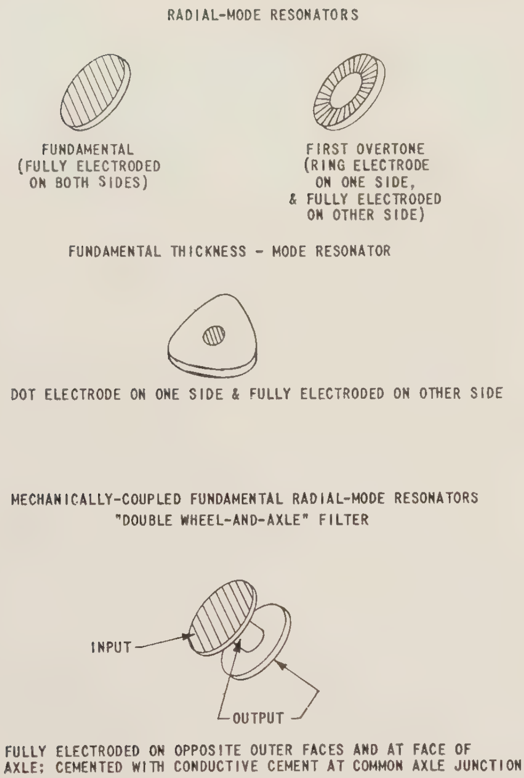
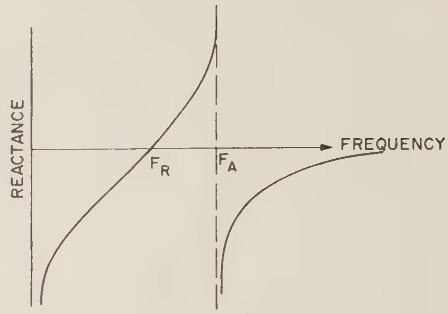
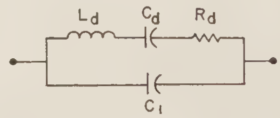


Fig. 14—Ceramic resonator elements.





TYPICAL VALUES FOR 455 KC	
Ld	22.7×10^{-3} HY
Cd	5.5 UUF
Rd	46.5 Ω
C_1	110 UUF

Fig. 15—Reactance and equivalent circuit of two-terminal ferroelectric ceramic resonator.

Ceramic Resonator Elements [11], [12]

In the approximate frequency range of 200 kc to 4 Mc there have been many resonant element structures and configurations attempted in the past few years. In general, the following simplest geometries have worked best: the fully electroded disk operated at its fundamental radial-mode, the first overtone, the fundamental thickness-mode resonator. These configurations are shown in Fig. 14. The resonant frequency of radial mode elements is primarily dependent on the diameter of the disk. As a practical consideration, it has been found best to keep the thickness-to-diameter ratio at less than one to four. With larger ratios, spurious response becomes a problem and for small ratios the element becomes somewhat fragile. In the thickness mode, the resonant frequency is inversely proportional to the thickness with the other dimensions chosen to minimize spurious content. The triangular configuration was found to reduce the unwanted modes of vibration. Fig. 14 also shows an interesting variation, the "wheel-and axle" [10], which is a complete band-pass filter with impedance transformation capability. This configuration has not been fully exploited, largely because the simple, fundamental-mode disk is economically more feasible at the present time.

The reactance characteristics of a fully electroded disk in the region of its fundamental radial mode of vibration is shown in Fig. 15. The zero or series resonant point at Fr is followed by the pole or antiresonant point, Fa. In the equivalent network, L_d, C_d, and R_d, are functions of the dynamic mechanical properties—mass, compliance, and internal frictional losses. C_1 is the static capacity.

The fully electroded radial-mode disk is the simplest to produce and shows the cleanest spurious-free characteristics, but it has size limitations which dictate the use of other modes. Below 200 kc, size becomes larger than one might call subminiature. Above one megacycle size becomes so small as to be too costly to be competitive with conventional parts. Fig. 16 shows the critical frequency determining dimensions and the corresponding frequencies for various geometries and vibration modes.

The values chosen are approximate and were dictated by considerations of ultimate production feasibility, miniaturization and ruggedness. For example, both thickness and length are frequency determining in the free-free flexural mode. Consequently, the sizes shown for that mode reflect an arbitrary decision that, for the sake of greater mechanical strength, the thickness will vary from approximately 40 mils for the larger resonators to 10 mils for the smaller resonators. In the region of the pass band the behavior and equivalent circuit of the various geometries are similar to those shown in Fig. 15.

Filter Networks

In its simplest form, a single disk can be used as a resonant coupling element or as a replacement for an RF bypass capacitor with the additional property that in the region of low impedance at series resonance, signal transmission is favored; at other frequencies, higher impedance provides degeneration. However, the single resonators can also be used as building blocks for more sophisticated filter performance. Two fundamental disks connected in the form of an "L" make up a 3-terminal, coupling network [11], [13]. By adjusting the antiresonant frequency of the shunt disk to be equal to the res-

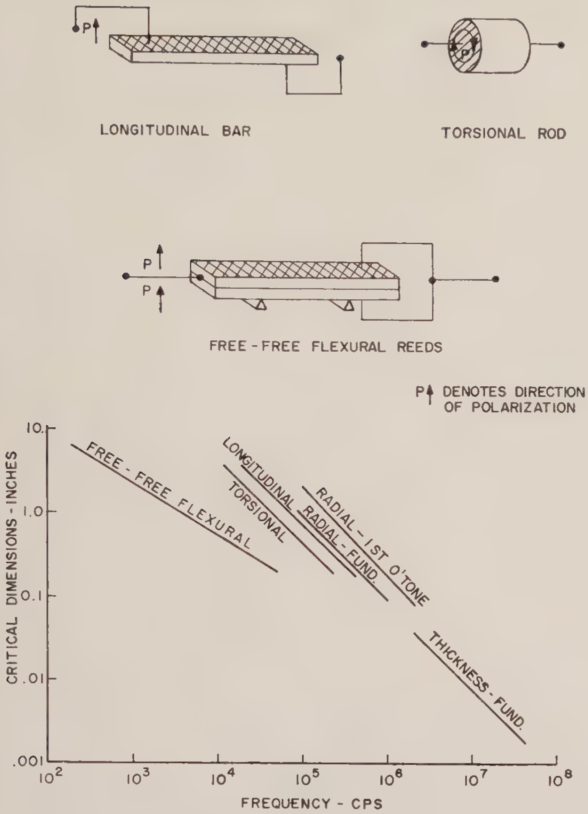


Fig. 16—Dimensions of practical resonators.

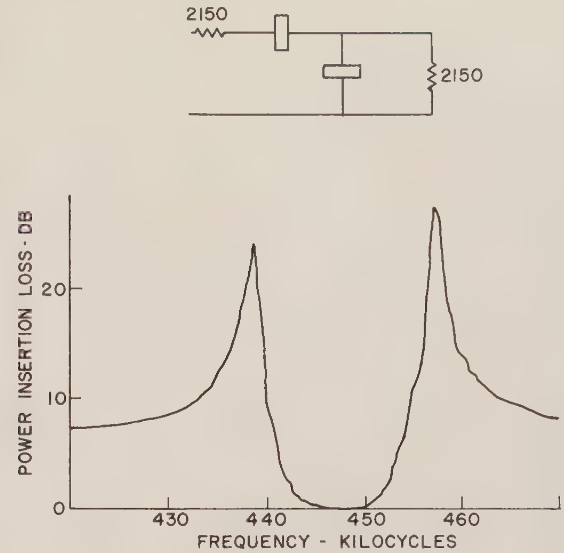


Fig. 17—Response of a section of a ladder filter.

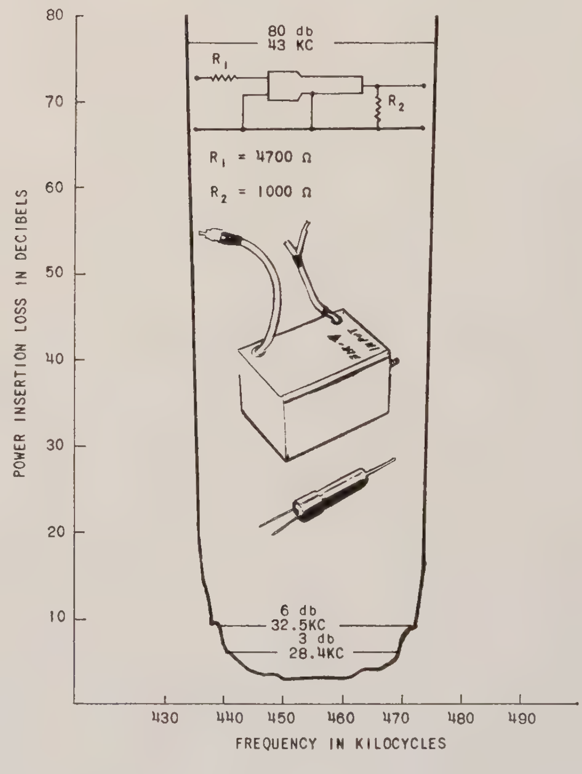


Fig. 18—Frequency response of 17-element ceramic filter.

onant frequency of the series disk, an elementary filter with band-pass characteristics is possible. Some control of input and output impedance is possible by varying disk thickness and by varying the degree of polarization. Bandwidth is affected by variations in thickness and polarization potential. A thicker shunt disk with lower static capacitance tends to widen the bandwidth and increase impedance. Used as a filter such an L section can give a response superior to a single tuned *LC* filter.

Cascaded L sections with steep skirt response such as shown in Fig. 17 can be formed into a multi-element ladder configuration with highly selective band-pass characteristics. Fig. 18 shows the response curve of one of the more complex forms, a 17-element ceramic filter. As a matter of interest the photographic inset compares the size of the ceramic filter (in the tubular case) with the conventional *LC* filter which it replaced.

Filter Termination

A proper match at the input and output terminals of the filter is desirable. A mismatched filter may introduce considerable band-pass ripple. A well-designed filter, one which is correctly terminated, will provide midband response with almost no evidence of ripple and low attenuation.

Miniature toroidal transformers and inductors can be employed as terminations to provide matching. Ceramic transformers are, to a limited degree, another expedient. The toroidal autotransformer is a simple and versatile means for impedance matching while simultaneously providing inductive compensation for capacitive source and load. This application of the autotransformer is effectively illustrated in Fig. 19, which shows the effect of mismatch which occurred when a conventional *LC* filter was replaced by a ceramic filter. It may be noted, incidentally, that in addition to providing a very wide, continuous range of impedance transformation (from a few ohms to over 50,000 ohms), it provides the dc path required for many applications. The inductance of the input transformer is designed to resonate

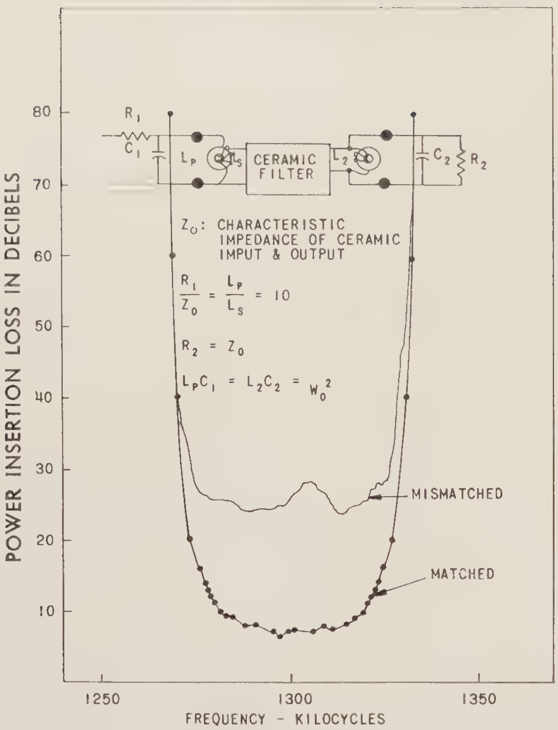


Fig. 19—Comparison of response with matched and mismatched termination.

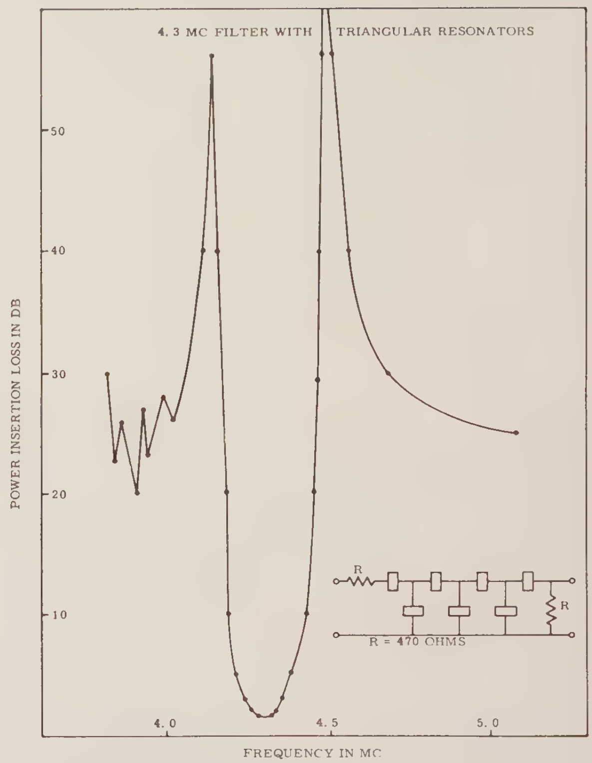


Fig. 20—4.3-Mc filter with triangular resonators.

with the source capacitance. The turns ratio is adjusted to match the source resistance with the input characteristic impedance of the filter. Finally, by resonating the output load capacitance with the shunting output inductor, it is possible to virtually eliminate band-pass ripple.

Higher Frequency Filters

With presently available fabrication techniques, it appears feasible to operate in the first overtone mode up to approximately 2 Mc where the disk diameter is about 0.12 inch. There is, however, recourse to other modes of vibration at higher frequency. For example, Fig. 20 shows the frequency response of an experimental model of a 4.3-Mc filter using seven triangular shaped thickness expander plates. As noted previously, the triangular shaped plate is found to reduce spurious vibrations. Masking (damping) of the disk faces in the form of a triangle appears equally effective in reducing spurious response. It is estimated that a 17-element filter would bring the response outside the pass band up to 60 db with negligible increase in midband insertion loss.

Work on the thickness mode type of resonator has led to a phenomenon with fascinating possibilities. As was noted above on the 4.3-Mc thickness mode resonators, spurious modes can be effectively reduced by the application of damping material at some minimum distance from the electroded area of resonance. This was accomplished without any significant degradation in the performance of the wanted mode. Taking this process one step further, it seems logical that if spurious modes can be disregarded or controlled, a number of resonators can be placed on a single ceramic wafer without interaction, provided they are sufficiently distant from each other. Such a technique was successfully applied in a multiple resonator structure, where the fundamental frequency of each element is about 10 Mc. Specifically, some experimental thickness mode filter sections operating at 10.5 Mc were successfully fabricated. This technique is quite new and requires refinement. However, the potentialities are considerable. Truly solid-state circuits are possible by poling discrete portions of a ceramic wafer for resonant operation and metallizing other portions for either circuit interconnections or to introduce capacitance (the ceramic is an excellent Hi-K dielectric). Resistors where needed can be added by doping the ceramic or by well-known metallizing techniques. In fact, even active elements such as transistors can be placed on the ceramic. Fig. 21 shows the excellent response characteristics obtained on an early experimental model of a single "T" section of such a multielement wafer [19].

Ferroelectric Transformers

In addition to the use of ceramic resonators as two-terminal elements, by properly oriented electroding a single resonator can be converted to a four-terminal element and impedance transformer. To perform this conversion the electric field pattern produced by stand-

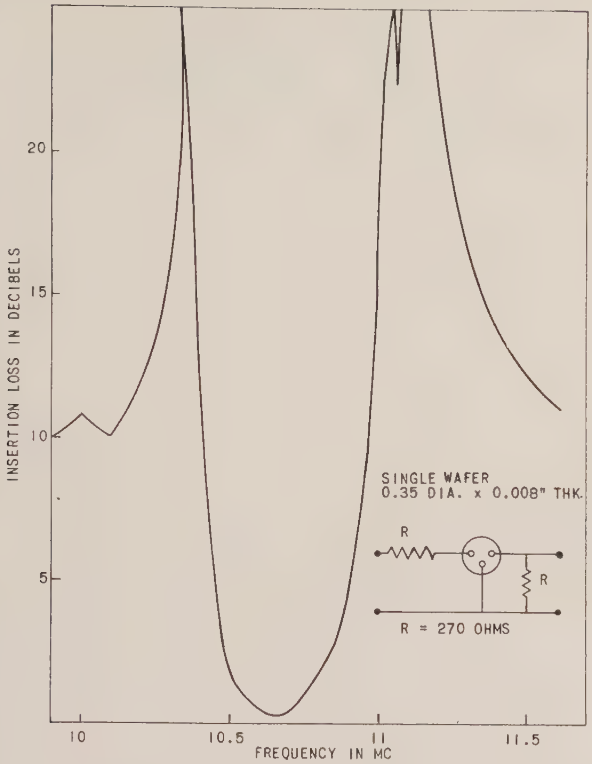


Fig. 21—Multi-electroded ceramic wafer.

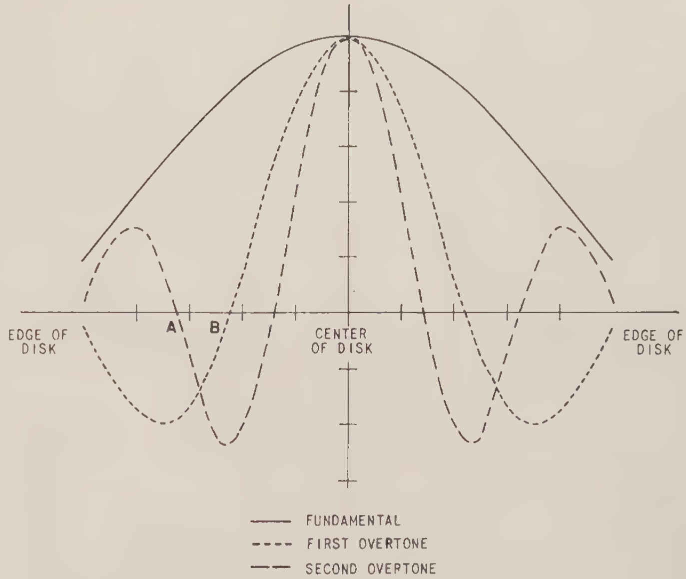


Fig. 22—Relative electric field strength vs radius of a radial-mode disk. The use of "first overtone" and "second overtone" here is in the musical, or acoustic sense. The convention used in the crystal field would replace these names with "second overtone" and "third overtone," respectively.

ing waves in a resonant structure is utilized to provide impedance transformation. Shown in Fig. 22 are the electric field strength patterns in a thin disk. Because the overtones show a voltage inversion in the regions marked *A* and *B*, a ring electrode can be oriented to suppress one of the overtones. The position and relative area of the outer ring and inner dot electrodes can control impedance levels. Under matched conditions, impedance ratios up to 25 to 1 are possible with first overtone disks. At 455 kc the characteristic impedance at the maximum ratio is approximately 200 ohms at the low side and about 5000 ohms at the high side. Considerably higher ratios can be achieved with other configurations.

Such transformers also have possibilities for delivering reasonable power, possibly in the order of 20 watts for a single resonator. Because of the two-dimensional nature of ceramic resonators, particularly in the radial mode, heat dissipation capabilities of such a unit are superior to those of a conventional core and coil transformer which approaches a cube for optimum design. For high voltage transformation, a long creepage path is inherent at the high voltage end of a longitudinal ceramic resonator. This is another feature that might possibly be exploited to advantage. In such a design, transformer and insulator are one and the same. Considering the size of a 10,000 volt insulator, such a size saving can be considerable for such uses.

Essentially, the ceramic transformer is a narrow-band device, unlike conventional core and coil power transformers. Spurious modes are not as important a consideration as they would be in filter devices. However, a shift in resonant frequency, caused by heating, can have a very serious effect on output voltage and regulation. Similarly, output voltage is sensitive to loading.

Lower Frequency Resonators

The simple radial and longitudinal modes of vibration used in the frequencies above 100 kc are not suited for low frequencies because size increases rapidly. This can be seen by extrapolating the curves on Fig. 16. In these simple modes of vibration the frequency determining dimensions of the resonators are, for any given mode, linearly proportional to wavelength. For example, a 92-kc fundamental radial mode resonator is about one inch in diameter and the longitudinal mode rectangular plate is also about one inch long. At frequencies below 10 kc, dimensions would have to be measured in feet rather than inches. Some alleviation of this problem can be achieved by using a torsional mode, with a reduction of about 40 per cent compared with the length of a longitudinal rod. Considerable size reduction of resonators can be accomplished through the use of flexural or bending modes. Bending vibrations can be produced in a reed by cementing two thin ferroelectric ceramic plates together with a conductive cement. A bending moment is produced if one of the slabs is elongated with respect to the other.

At the lowest frequencies, mass loading of thin reeds is a technique which permits considerable miniaturization. When one considers the long period of a watchspring and balance wheel, it may be clearly appreciated that old arts and skills are adaptable to many of our newer and more stringent demands for reduced size.

Ultrasonic Delay Lines

The ferroelectric, magnetostrictive and acoustic phenomena are also applicable to delay lines as well as filters and transformers. These approaches provide a means for attaining large delays in a small, low cost, reliable device. A particularly interesting approach is one which closely parallels the operation of the electromechanical filter, with the exception that resonant operation is not desirable. The electrical signal is converted to an acoustic wave which is propagated along a stable nickel-alloy wire. The receiver transducer is placed at a given distance along the line proportional to the desired delay. Such media provide a delay of approximately 5 microseconds per inch when the signal is propagated longitudinally. The slower torsional propagation provides 35 to 40 per cent size reduction. A transducer which propagates such a wave can be realized from the torsional resonator previously discussed. In this way the success of such resonator work has two-fold application possibilities, as a filter and transducer. There is the additional advantage of lower loss to be realized from the use of a ferroelectric transducer. Present techniques using a coil coupled to the delay line result in approximately 20-db loss in each transducer. A direct coupled transducer such as a ferroelectric drive should reduce this loss considerably.

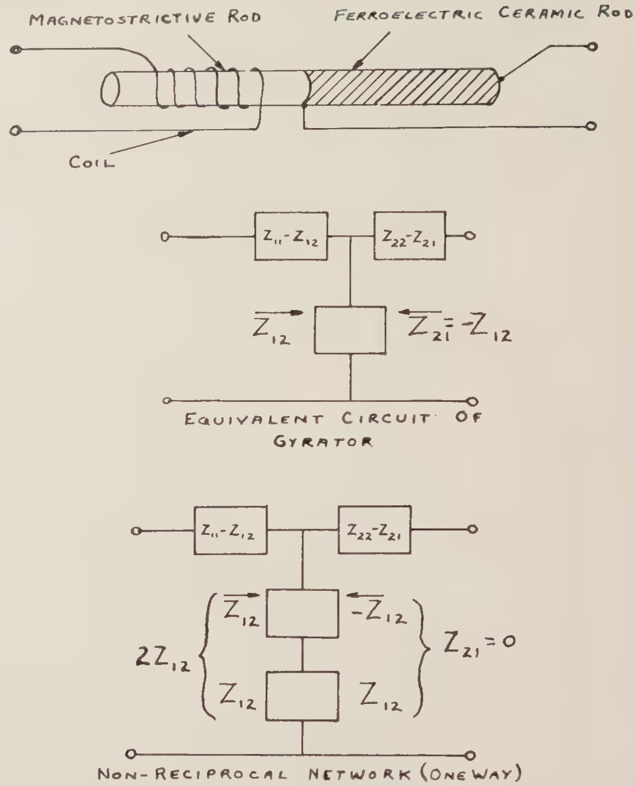


Fig. 23—Electromechanical gyrator.

Electromechanical Gyrator

The ideal gyrator [18] is a passive device in which the mutual impedance component displays a phase reversal in one direction only. This antireciprocal property of the gyrator can be utilized to provide decoupling between the input and output of a network by the addition of a reciprocal impedance in series with the antireciprocal mutual impedance (Fig. 23). By mechanically coupling a magnetostrictive driving transducer to a ferroelectric ceramic output transducer (Fig. 23), a low frequency form of a passive gyrator is possible. Because such a structure displays rather sharp regions of mechanical resonance where impedance changes rapidly with respect to frequency, the operating bandwidth is limited. Wide-banding of these devices is also a subject of present investigations. Complete data are lacking at this time; however, compared with the input signal, reverse transmission reduction of greater than 50 db is attainable.

Conclusion

As seen from the necessarily limited discussion on a somewhat extensive effort on solid-state electromechanical electronic parts, the potentialities are considerable. What is particularly rewarding is that the same research and development effort on the fundamental resonator or transducer elements forms the basis for a multitude of useable parts. For example, the ferrolectric ceramic resonator provides a transducer for the electromechanical filter, a transformer, a filter in its own right, transducers for delay lines, etc. The magnetostrictive ferrite used as a transducer for electromechanic filters has possibilities as a filter element, particularly where Q's of the order of 5000 are needed. It is also employed as a part of the low-frequency gyrator.

We would also like to note that the devices discussed herein are not projections, but real items which are, in many instances, already incorporated in electronic gear. Fabrication is possible by known and available production techniques and facilities. Also, the parts as they become available are not only in many respects superior in performance and size, but, what is particularly significant in a time of increasing military costs, they are competitive with the conventional electronic parts which they replace.

With present interest in microminiaturization, microelectronics, molecular engineering and other frighteningly complex and expensive approaches to size reduction and functional circuits, the electromechanical approach discussed herein provides some refreshingly simple low cost solutions. The very simplicity of the solid-state elements is evidence that this is truly molecular engineering. For, as opposed to the use of discrete identifiable parts, a simple geometric shape performs a complex function normally performed by a multitude of conventional electronic parts.

Acknowledgment

The authors would like to express their appreciation to D. Curran, of the Clevite Research Center, Cleveland, Ohio, D. Lundgren of RCA, Camden, N. J., and Dr. S. Tehon, of General Electric, Syracuse, N. Y., for their helpful criticism, and to R. Sproat, USASRDL, Fort Monmouth, N. J., for his considerable assistance.

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Electron Tubes and Devices in the 4.3-mm Frequency Range*

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***Summary*—This paper discusses the development programs for a klystron, a magnetron, and various duplexing and switching devices for the 70-kMc region of the radio frequency spectrum during the last decade. An evaluation of the electrical performance and of the behavior under environmental conditions for these devices is also discussed. It is concluded that the quality and performance of the devices make system application feasible. Sections I and II describe the klystron and magnetron program. Section III describes the switching devices program.**

Introduction

IN the last decade, interest in utilization of the millimeter-wave region of the radio spectrum has grown tremendously. This interest is primarily due to the desire by the military to open new and unused portions of the spectrum, in order to relieve the serious radio traffic congestion which exists at lower frequencies such as *S* and *X* bands; and partly to the desire to capitalize on the high resolution and small antenna size that can be realized in radars at millimeter-wave frequencies.

Another potential application in which millimeter waves might be used advantageously is the area of secure point-to-point communication. In certain regions of the millimeter-wave portion of the spectrum, absorption of RF energy by the oxygen and water vapor of the atmosphere is appreciably higher than at other portions of the spectrum. This increased atmospheric attenuation, coupled with the increased directivity of practical-sized millimeter-wave antennas, makes possible the design of a secure point-to-point communication link.

The programs described in this paper, covering development of a reflex klystron, a pulsed magnetron transmitter tube, and various types of duplexing and switching devices, started in 1951 at several industrial laboratories. Some of the development work on the klystron and magnetron was based on earlier work by the Raytheon Company on a 5-mm klystron and by Columbia University on a 4-mm magnetron. It is interesting to note that a portion of each millimeter device program was devoted to the development of attenuators, slotted lines, tuning sections, crystal and thermistor mounts, and other millimeter-wave components. These components, at that time, could not be purchased as shelf items; but were, nonetheless, necessary in the design, testing, and evaluation phases of the device programs. Major emphasis in the first stages of the program was on the early completion of sample klystrons, since these samples were urgently needed as signal sources by the other device developers.

By 1954, the development phases of the three programs were successfully completed and samples were available. Efforts on these devices since that time have been concentrated on improving performance, ruggedness, life, and reliability. Details of past and present performance are discussed in Sections I, II, and III.

* Received by the PGMIL, July 11, 1960.
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I. 4.3-MM Klystron

The first available klystron for wavelengths shorter than 5 mm was the QK-369 reflex klystron, developed commercially under Signal Corps sponsorship.[1] This tube, shown in Fig. 1, was designed to operate at 4.3 mm. Prior to the development of the QK-369, the QK-295 klystron typified the tubes available for operation up to 5.0 mm. Designed for operation at 5.0 to 5.5 mm, the QK-295 required an anode voltage of 3500 volts, and yielded a power output of less than 0.5 mw. Operation was unreliable, and precise tube adjustments were required before oscillations could occur. The QK-295 was a scaled version of an earlier type (2K33) developed in England and used extensively during World War II, and therefore did not represent a significant advance in the state of the art.

The QK-369 klystron, although evolved from the same prototype as the QK-295, soon demonstrated that new techniques of processing and fabrication were necessary if low voltage operation was to be achieved. For example, as a tube is scaled to higher frequencies, the processing and fabrication become increasingly difficult, since the tolerances of the dimensions of the tube parts must likewise be scaled.

The most serious problem in scaling is that posed by the cathode. In the QK-369 the use of "L" type cathodes was an absolute necessity to insure the high current emission densities required.

By diligent investigation of the techniques for forming and processing impregnated cathodes, the lifetime of the QK-369, which was poor in the early stages of the program, has been improved considerably and now compares favorably with lifetimes of commercially available lower frequency klystrons. In a recent life test of fifteen QK-369 tubes, twelve exceeded the required 500-hour minimum life requirement.

One of the processing techniques used to good advantage was that of cold-hobbing the resonator. This technique achieved "micro-finished" internal cavity surfaces, a type of finishing found to be essential in keeping RF losses in the miniature cavity to a minimum. Since all parts are designed to be self-jigging and are fabricated with optical precision, they fit together well enough to obviate the necessity for skilled assemblers and assembly jigs to provide the required optical alignment of the gun aperture and repeller.

Although the original objective was a tube requiring only 1000 volts of anode potential, this low voltage has not yet been achieved. However, tubes have been operated successfully at voltages as low as 1200 volts, and normally operate with no more than 1400 volts on the anode.

Early models of the tube produced only a few milliwatts; recently, however, an evaluation[2] was made of thirty QK-369 klystrons, and many of these tubes had exceptionally good power outputs. As shown in Fig. 2(a), 67 per cent had a minimum power output of 30 mw, and all thirty had a minimum output of 17 mw or greater. Maximum power output was recorded near the center of the tuning range, and minimum output was recorded at the low frequency end.

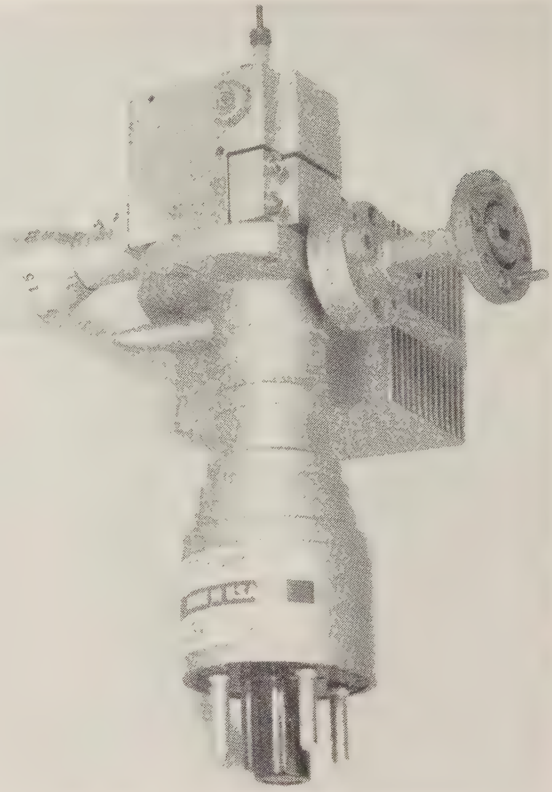

Fig. 1—4.3-mm reflex klystron, QK-369.

The QK-369 incorporates a focusing grid which is negative with respect to the cathode. This focusing grid was designed to operate at -125 volts. Fig. 2(b) shows that 60 per cent of the thirty tubes evaluated had voltage spreads lying within ± 15 volts of a mean value of 130 volts.

In some of the first tubes built, hysteresis was a problem. However, during the recent evaluation program, the maximum hysteresis observed was 20 per cent. As shown in Fig. 2(c), 50 per cent of the thirty tubes tested had less than 1 per cent hysteresis, and 94 per cent had less than 10 per cent. In view of the amount of hysteresis present in lower frequency tubes, the values obtained by the QK-369 are satisfactory.

The evaluation program also provided data on the QK-369's electronic tuning range and modulation sensitivity. As shown in Fig. 2(d), some tubes had very wide electronic tuning ranges. All thirty tubes had ranges of at least 75 Mc, and 18 per cent had ranges as high as 200 Mc. As shown in Fig. 2(e), the modulation sensitivity (frequency control by reflector voltage) at the linear electronic tuning region of the tube lies between 2.7 and 7.3 Mc/volt for the thirty tubes tested.

[1] U. S. Army Signal Corps Contract No. DA 36-039 sc-5523, Raytheon Co., Waltham, Mass.

[2] U. S. Army Signal Corps Contract No. DA 36-039 sc-74909, Raytheon Co., Waltham, Mass.

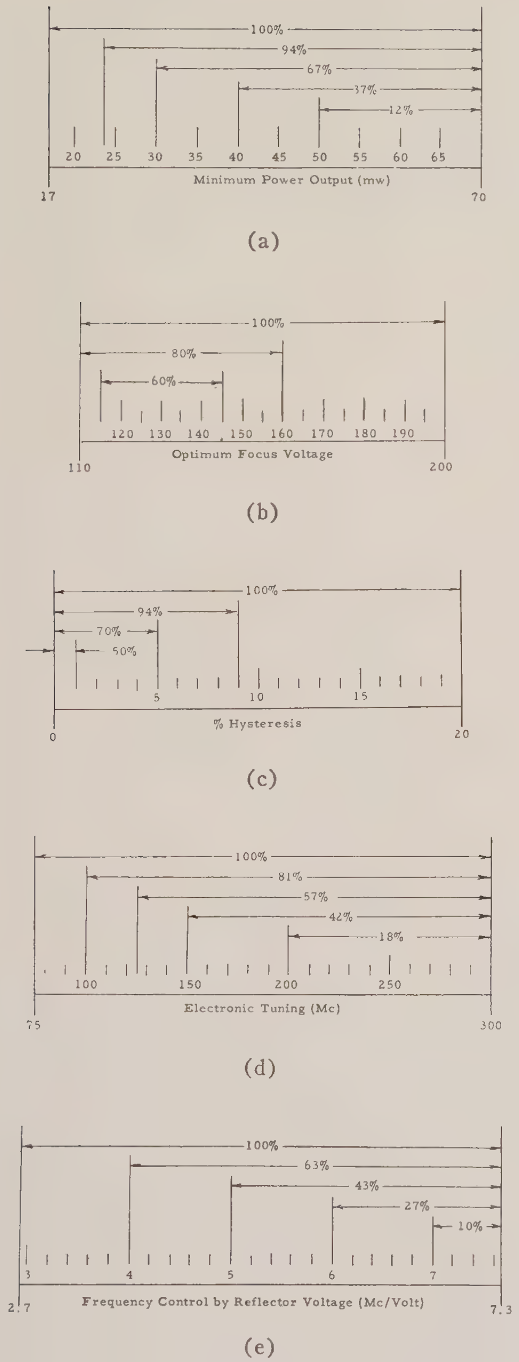

Fig. 2—Results of evaluation of thirty QK-369 klystrons.

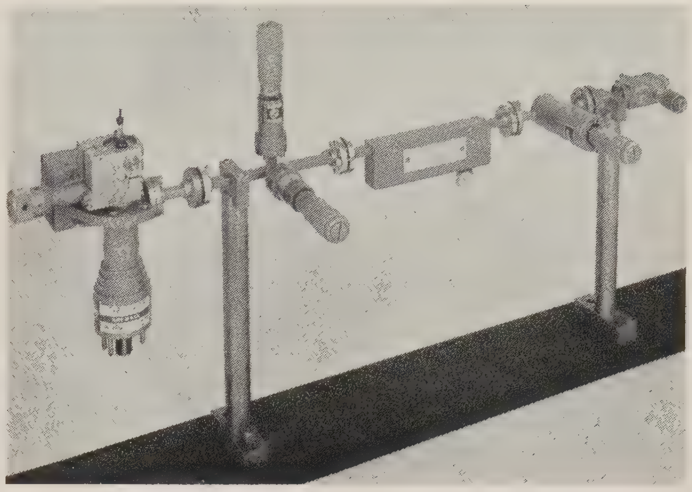

Fig. 3—Experimental test setup for measurements of QK-369 klystron.

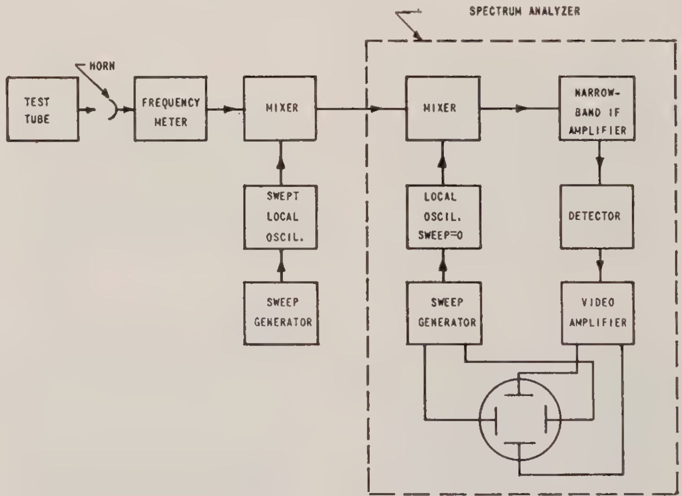

Fig. 4—Block diagram of the modified spectrum analyzer.

A typical setup of the millimeter-wave components used for measuring the parameters discussed above is shown in Fig. 3. The components (from left to right) are a QK-369, E&H tuner, attenuator, wave meter, and crystal mount.

Fig. 4 shows a block diagram of the modified spectrum analyzer used in measuring results of shock and vibration tests at USASRDL. The normally swept local oscillator of the spectrum analyzer was operated under CW conditions. A crystal mixer and additional QK-369, which served as a local oscillator, were placed in front of the input to the spectrum analyzer. The signal from the tube under test mixed with the signal for the QK-369 local oscillator. The mean frequency of the local oscillator and the frequency of the test tube were selected so that the difference between the two signals, which can be considered an intermediate frequency, fell into the lowest possible RF band of the analyzer, in this case 1150 Mc.

The tube was vibrated at accelerations of 1, 3, 5, 7, and 10 g's in two planes, perpendicular to the main axis and parallel to the main axis. For each acceleration the vibration frequency was varied from 10 to 2000 cps.

A large number of mechanical resonances were observed during vibration. The worst cases appeared from 600 to 800 cps and from 1400 to 1700 cps, and caused a wide spectrum on the screen, as shown in Figs. 5(b), 5(d), 6(b), 6(c), and 6(d). At low vibrating frequencies the spectra were narrow, as shown in Figs. 5(a), 5(c), and 6(a). Between the resonance points the tube operated like a normal CW oscillator.

The 4.3-mm klystron development represents a considerable advance in the state of the art in the design and

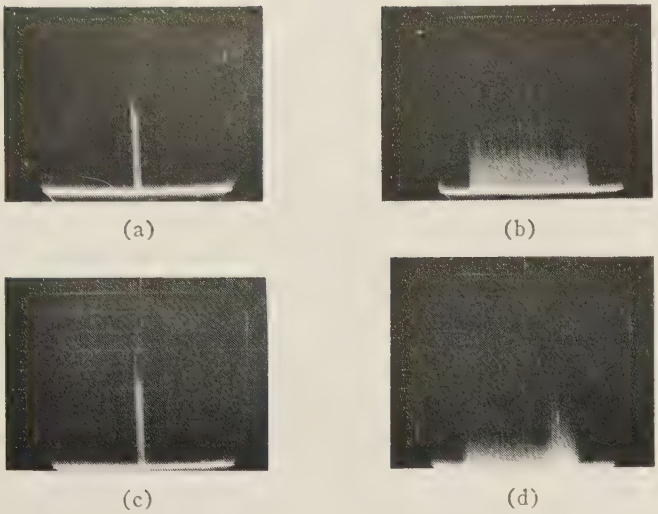

Fig. 5—QK-369 klystron vibrated perpendicular to main axis. (a) Vibration frequency (VF): 790 cps, $G=1$; width of spectrum (WS): 2 Mc. (b) VF: 1550 cps. $G=5$; WS: 160 Mc. (c) VF: 50cps, $G=10$; WS: 3 Mc. (d) VF: 1190 cps, $G=10$; WS: 170 Mc.

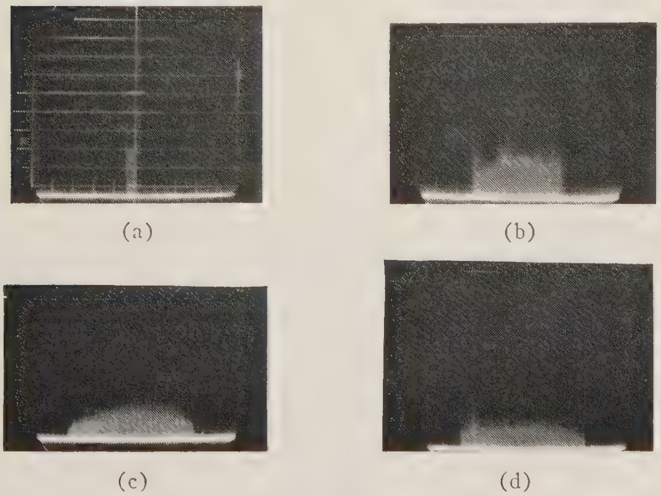

Fig. 6—QK-369 klystron vibrated parallel to main axis. (a) Vibration frequency (VF): 480 cps, $G=1$; width of spectrum (WS): 6 Mc. (b) VF: 800 cps, $G=5$; WS: 80 Mc. (c) VF: 1610 cps, $G=7$; WS: 140 Mc. (d) VF: 1660 cps, $G=10$; WS: 150 Mc.

construction of millimeter-wave klystrons. The processes developed under this program are now used to build klystrons operating at even shorter wavelengths. Power levels up to 150 mw at sufficiently long life times were obtained, electronic tuning performance is satisfactory, and hysteresis has been minimized.

Reduction of mechanical resonances, especially in the tuner, and the design of a more rugged heater are areas still requiring further improvement to provide a more mechanically reliable tube. It is important to note, however, that, in spite of these mechanical deficiencies, the tube was still electrically sound after being vibrated at frequencies as high as 2000 cps and at accelerations as high as 10 g's. Other recently developed millimeter klystrons failed to operate after being subjected to much less severe vibration conditions.

II. 4.3-MM Pulsed Magnetron

In 1951, the Signal Corps initiated a program[3] for the development of a 4.3-mm magnetron and the construction of a number of preproduction samples for laboratory use. This development was based upon previous work at Columbia University, and resulted in a pulsed 4.3-mm magnetron, designated the BL-201.

The BL-201 is a fixed-frequency, air-cooled tube capable of a minimum peak power output of 8 kw at 0.00025 duty cycle. The tube operates at a peak current of 12 amperes at approximately 11 kv with a nominal efficiency of 8 per cent. Fig. 7(a) shows an early design, and Fig. 7(b) shows the final version of the BL-201.

Although the BL-201 is a valuable laboratory tool, it lacks the electrical and mechanical characteristics necessary for anticipated military application. Therefore, in 1957 the Signal Corps initiated a contractual program[4] for the development of an improved 4.3-mm magnetron, designated the BL-221, shown in Fig. 7(c). As a result of this program, the following objectives were achieved:

1) improved environmental capability,
2) increased duty cycle capability,
3) increased peak power output,
4) reduced size and weight,
5) improved life.

The BL-221 magnetron is essentially a scaled version of a 5.4-mm magnetron. The tube utilizes a 38-vane, semi-closed, "rising sun" anode, as shown in Fig. 8. The anode is hot-hobbed, and is machined by special techniques which provide an anode free of burrs. A Philips type B cathode, which is supported by a cantilever structure, is employed. To insure concentricity of the anode, cathode, and pole pieces, the tubes are X-ray inspected before final assembly. A unique feature of 4.3-mm magnetrons is the cathode-centering mechanism, which is adjusted and sealed by the manufacturer. Since the tube parts are small and the cathode position critical, cathode-centering after the tube has been processed is a necessity, and is accomplished during initial starting.

The more important electrical characteristics of the BL-221 magnetron are:

fixed frequency: 69,000 to 70,500 Mc,
duty cycle: 0.0005 (minimum),
pulse duration: 0.03 to 0.3 μsec,
rate of rise of voltage: 450 kv/μsec (maximum),
peak current: 7 amperes,
peak voltage: 12 to 13.5 kv,
peak power output: 10 kv (minimum),
pulling factor: 75 Mc (maximum),
life: 120 hours (minimum).

[3] U. S. Army Signal Corps Contract No. DA 36-039 sc-71188, Bomac Labs., Beverly, Mass.

[4] U. S. Army Signal Corps Contract No. DA 36-039 sc-73285, Bomac Labs., Beverly, Mass.

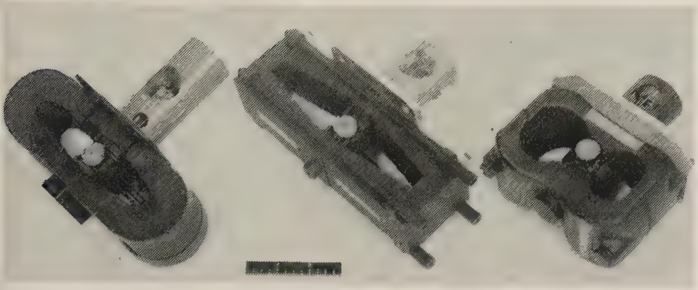

Fig. 7—4.3-mm pulsed magnetrons. (a) BL-201, early design. (b) BL-201, final design. (c) BL-221 4.3-mm magnetron.

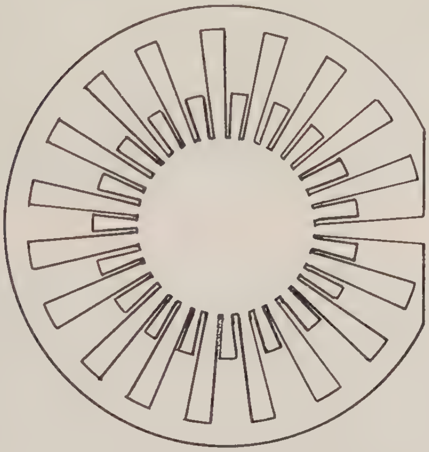

Fig. 8—38-vane anode.

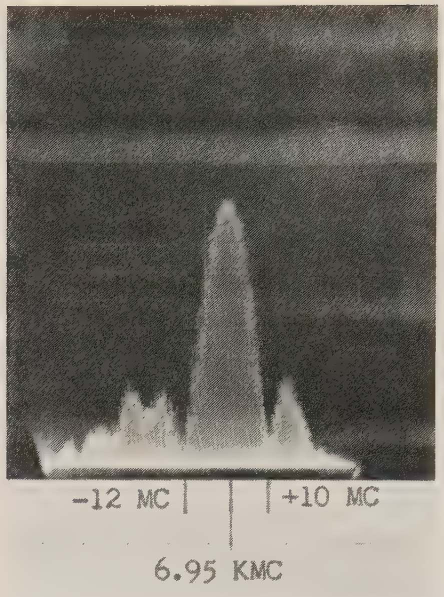

Fig. 9—Typical spectrum of BL-221 4.3-mm magnetron.

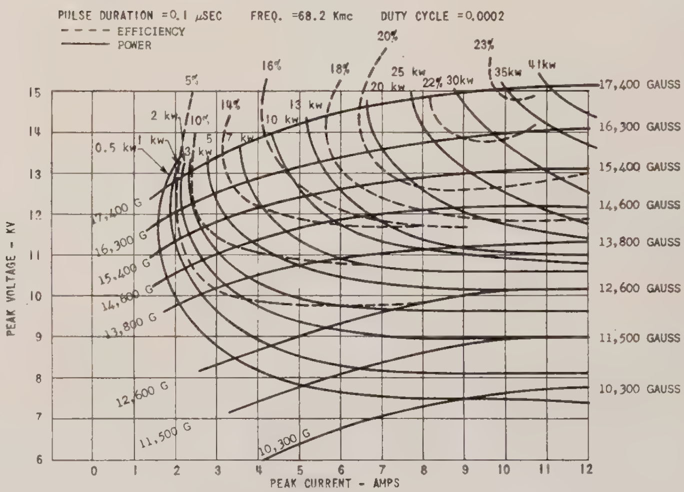

Fig. 10—Magnetron performance chart (BL-221 No. 127).

At short pulse durations, in the order of 0.03 μsec, peak and average currents do not always correlate, because leakage and capacitive-charging currents become significant. Under these conditions, the peak rather than average current is used as the criterion for adjusting the tube to the proper operating point.

Average power output of the BL-221 magnetron is limited to 8 or 10 watts, a limitation imposed by the power-handling capability of the glass RF output window. Fig. 9 shows a typical spectrum, obtained with a 0.1-μsec pulse. The characteristics of the BL-221 are shown in Fig. 10, a magnetron performance chart. Since the cathode heating caused by back bombardment changes with duty cycle and pulse duration, the applied heater voltage must be adjusted to maintain the correct cathode temperature.

Environmental capabilities of the 4.3-mm magnetron were improved by the use of a shorter cathode supporting structure and by replacement of the glass high-voltage bushing with a ceramic bushing. The environmental capabilities of the BL-221 are as follows:

shock: 50 g, 4 msec duration,
vibration: 10 g, from 5 to 50 cycles,
low temperature operation: −55°C.

From a physical standpoint, the 4.3-mm magnetron has been improved in several ways. By use of more efficient magnets, the size and weight of the magnetron were reduced. The tube was equipped with an output flange containing an RF choke and a rubber gasket (the gasket permits pressurization of the waveguide). The output flange support was also improved so that it can withstand a greater mechanical strain than the BL-201 flange. The more important physical features of the BL-221 are:

weight: 7.5 lbs (maximum),
volume: 70 cubic inches (maximum),
cooling: air,
mounting: any position,
mating flange: UG-385/U (modified to mate with output flange),
waveguide: RG-98/U,
input connector (heater-cathode): Ucinite type 115364 connector.

The BL-221 magnetron is superior to the BL-201 both electrically and mechanically. Electrically, it is capable of generating a peak power in excess of 10 kw at 0.0005 duty cycle. While several tubes have been life tested for a minimum of 120 hours without failing, additional life testing is necessary to verify reliability. Mechanically, the tube has been ruggedized and is now suitable for installation in mobile systems.

III. 4.3-MM Switching and Duplexing Devices

Gas-Discharge Duplexers

Branched Duplexer:[5] The original duplexer developed for use with a millimeter radar system was designed for operation at the 4.3-mm-magnetron power output levels (about 10-kw peak), and consisted of a fixed-tuned ATR tube and a tunable TR tube permanently mounted in a section of rectangular waveguide. The branched duplexing unit thus formed has three rectangular waveguide terminals. One connects to the radar system transmitter, the second to the radar system antenna, and the third to the radar receiver system. A photograph of the disassembled duplexer, showing the TR tube, ATR tube, and waveguide mounting section, is presented in Fig. 11, and the assembled duplexer is shown in Fig. 12.

The ATR tube is a rectangular cavity which is nominally one-quarter of a guide-wavelength long, with a rectangular input resonant window in the input face. It is mounted flush with the inner waveguide wall. A brass gas reservoir with a volume many times that of the ATR cavity is provided to insure against gas cleanup during operation. The gas fill consists of an argon water-vapor mixture at a pressure of 40 mm of mercury.

The TR tube is of the conventional integral cavity design. It is mounted three-fourths of a guide wavelength from the ATR tube. The input face of the TR tube is one-half of a guide wavelength from the inner wall of the waveguide mounting section.

Two unique features incorporated in the TR tube design are a full-wavelength radial choke at the movable tuning cone and a half-wavelength radial choke at the window. The choke at the cone makes it possible to use a large-diameter sealing diaphragm, which permits the required cone travel without danger of diaphragm rupture. The choke at the window was necessary in order to eliminate the problems associated with poor electrical contacts.

The tube is tunable through a frequency range of 68.75 kMc to 70.75 kMc, with a gap spacing of 0.001 inch at the low frequency end of the band, and 0.003 inch at the high frequency end.

A side-arm ignitor electrode is incorporated in the design to minimize the spike leakage energy through the tube. A gas reservoir in the form of a glass bulb is attached to the TR tube structure to insure against gas cleanup during operation. The gas fill consists of an argon, xenon, water-vapor mixture.

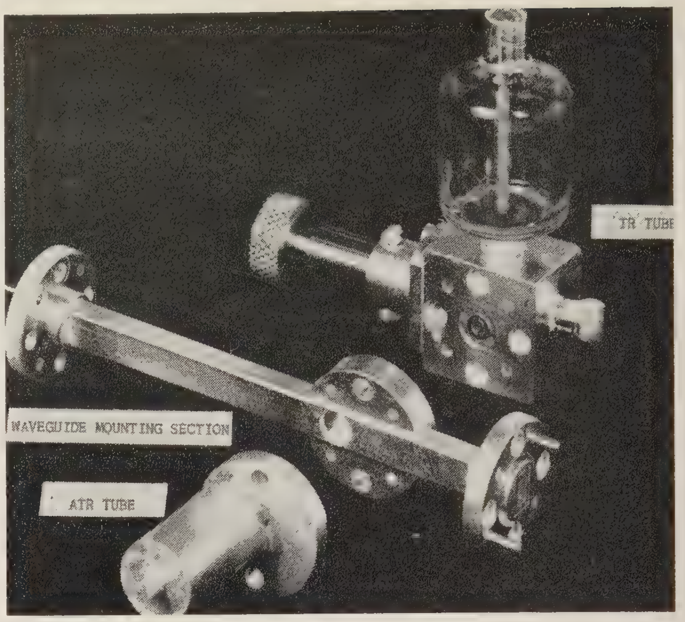

Fig. 11—4.3-mm duplexer, branched type (BL-24), exploded view.

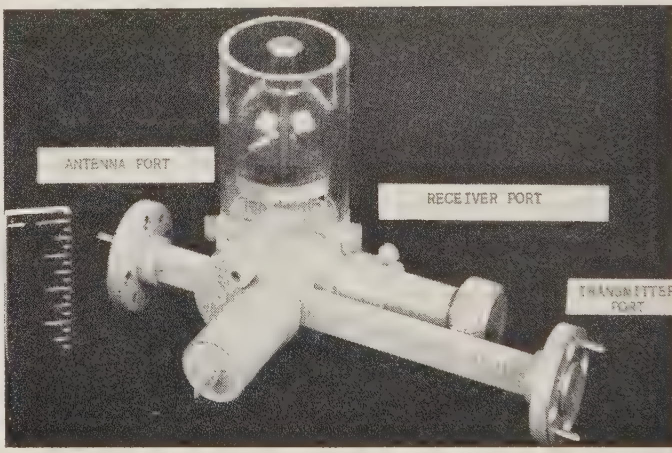

Fig. 12—4.3-mm duplexer, branched type (BL-24), over-all view.

The ATR and TR tubes must be treated as an integral duplexer unit because of the assembly, mounting, and electrical measurement problems inherent at this frequency range. All of the operating characteristics and design parameters must be defined in terms of over-all duplexer performance rather than separate and distinct TR and ATR tube characteristics. Neither the TR nor the ATR tube can be disassembled from the waveguide mounting section without seriously upsetting the electrical characteristics of the duplexer.

Several dozen duplexers have been made and used in the millimeter radar system. In general, duplexer performance and life have permitted reasonable system operation. Typical duplexer performance characteristics are given in Table I. As shown in the table, most of the parameters, such as VSWR, leakage characteristics, recovery time, and isolation between antenna and transmitter during the receive time interval, were satisfactory. However, low-level duplexer loss was higher

[5] U. S. Army Signal Corps Contract No. DA 36-039 sc-15417, Bomac Labs., Beverly, Mass.

TABLE I

Performance Characteristics Branched Type Duplexer (BL-24)

Duplexer No.	VSWR at Frequency (kMc) Indicated					Duplexer Loss (db) at Frequency (kMc) Indicated					Isolation (db) at Frequency (kMc) Indicated				
	68.75	69.25	69.75	70.24	70.75	68.75	69.25	69.75	70.25	70.75	68.75	69.25	69.75	70.25	70.75
1	1.18	1.17	1.16	1.37	1.38	2.5	2.2	2.0	2.3	3.8	19	22	28	19	15
2	1.35	1.20	1.04	1.22	1.34	3.6	2.8	1.5	3.1	4.6	14	23	30	20	13
3	1.15	1.13	1.24	1.21	1.26	2.4	2.8	1.7	2.0	2.6	15	18	24	25	20
4	1.28	1.15	1.11	1.15	1.28	3.3	2.3	1.9	2.9	3.5	14	21	30	21	15
5	1.12	1.11	1.10	1.38	1.60	2.6	2.4	2.1	2.7	3.5	15	21	28	24	16
6	1.15	1.14	1.15	1.10	1.08	2.5	2.1	1.6	3.4	4.4	13	18	26	25	16

TABLE I (*cont'd*)

Duplexer No.	Tuning Range (Turns)	Igniter Drop (v)	Igniter Interaction	Igniter Interaction Time (Seconds)	Flat Leakage Power (mw)	Spike Leakage Energy (Erg)	Arc Loss (db)	High-Level Insertion Loss (db)	Recovery Time (μsec)
1	3.5	415	Negligible	<1	26	0.02	1.0	1.3	<3
2	2.5	385	Negligible	<1	21	0.02	0.9	1.2	<3
3	5.0	375	Negligible	<1	28	0.02	1.1	1.3	<3
4	2.2	383	Negligible	<1	29	0.02	1.1	1.5	<3
5	5.5	415	Negligible	<1	29	0.03	1.2	1.6	<3
6	3.5	382	Negligible	<1	18	0.02	1.1	1.6	<3

than desired, particularly at the frequency band edges; high-level insertion loss, which includes the arc loss, was also high. To reduce these losses and thereby enhance system performance, a program was initiated for the development of a fixed-tuned, broad-band, balanced gas-discharge duplexer.

Balanced Duplexer:[6] A conventional design approach was taken in the development of the balanced duplexer. The device consists of a three-element, dual TR tube with a common gas fill. Two of the elements consist of resonant iris input and output windows, and the third element consists of an inductive post and capacitive cone. The dual TR tube is used in conjunction with a pair of 3-db, short-slot, hybrid couplers.[7] A photograph of a disassembled duplexer, showing the dual TR tube and the associated couplers, is presented in Fig. 13. A photograph of an assembled duplexer, complete with dual TR tube, couplers, and waveguide adapter arms, is shown in Fig. 14. Fig. 15 is an assembly drawing showing the design and construction of the dual TR tube.

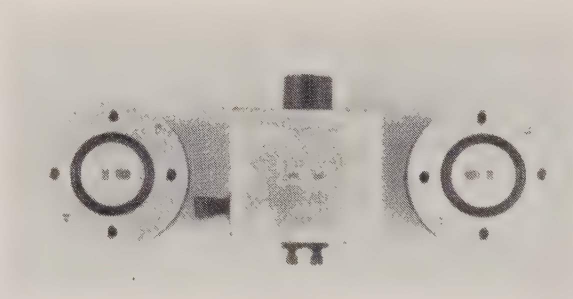

Fig. 13—Disassembled 4.3-mm duplexer, balanced type, showing dual TR tube and associated 3-db hybrid short-slot couplers.

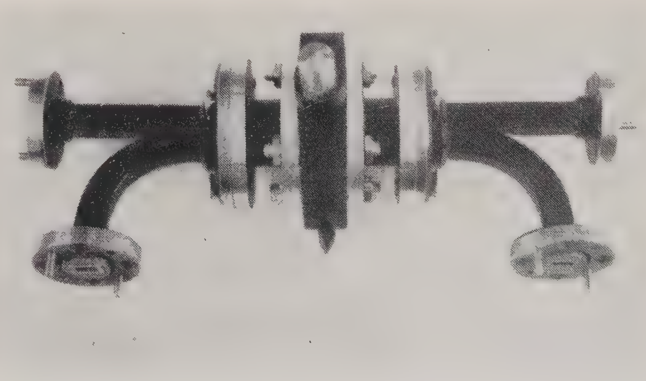

Fig. 14—4.3-mm duplexer, balanced type, showing dual TR tube, couplers, and waveguide adapter arms.

[6] U. S. Army Signal Corps Contract No. DA 36-039 sc-78285, Bomac Labs., Beverly, Mass.

[7] The couplers were designed by the Microwave Dev. Labs., Inc., Wellesley, Mass.

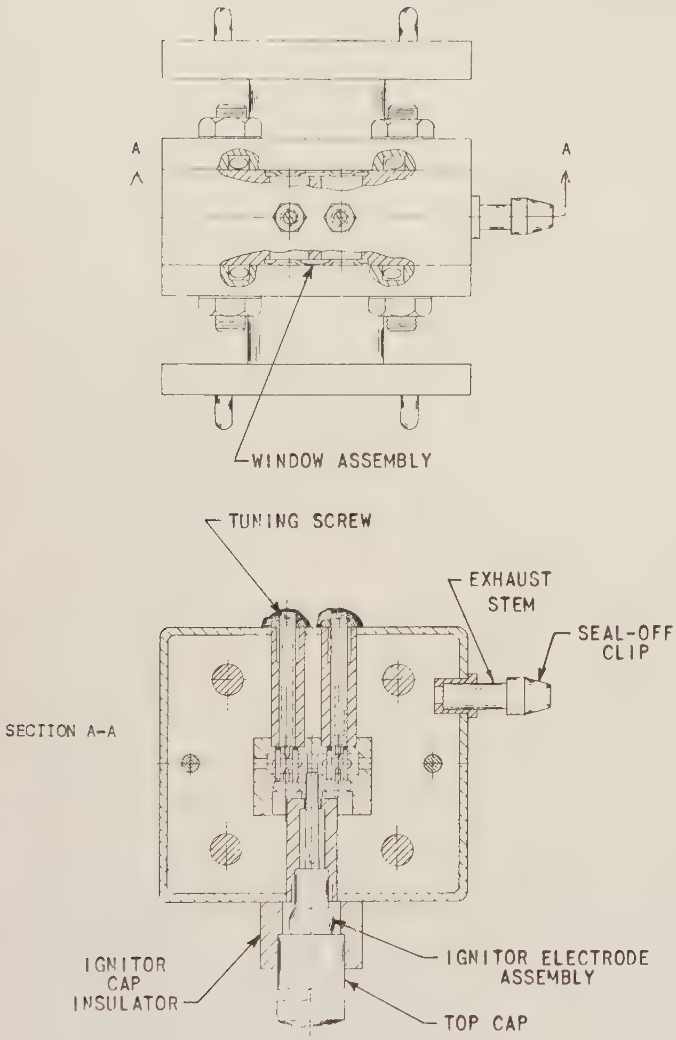

Fig. 15—Dual TR tube assembly.

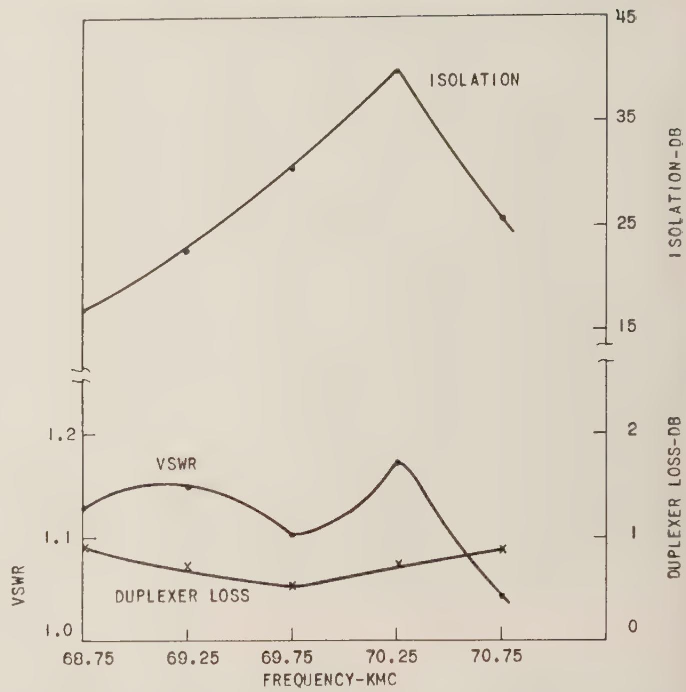

Fig. 16—MM dual TR tube, typical characteristics: VSWR, isolation and duplexer loss as a function of frequency.

The problems encountered were primarily those inherent in working with components in the millimeter frequency region. Small size and close tolerances imply a degree of fabrication and techniques control not ordinarily encountered.

Hobbed waveguide sections and an integral all-metal reservoir provide a rugged, basic design for the dual tube. A mixture of argon and hydrogen is used as the gas fill.

Several sample duplexers have been evaluated, and the results achieved are very satisfactory. Fig. 16 gives the typical low-power-level characteristics for duplexer loss, VSWR, and isolation over the frequency band. It will be noted that the performance is superior to that achieved previously with the branched duplexer. Other typical high-power-level performance characteristics are as follows:

spike leakage energy: 0.002 erg,
flat leakage power: 1.5 mw,
arc loss: 0.3 db,
recovery time: 1–2 μsec,
ignitor voltage drop: 220 vdc,
high power level VSWR: 1.2,
ignitor current: 100 μa.

These results were achieved under incident power level conditions of 15-kw peak power, 0.27 μsec pulse length, and 0.0005 duty cycle. Measurements made over an ambient temperature range of $-40°$C to 85°C and over an operational life of 500 hours have shown negligible degradation of pertinent characteristics.

Ferrite Devices and Crystal-Protector TR Tube

The great strides made during the past decade in research leading to the design of microwave ferrite devices have also resulted in the development of a line of millimeter ferrite devices.[8] These ferrite devices, an isolator, circulator, switch, and pulsed attenuator, can be used in various combinations to provide the duplexing and switching functions required in millimeter electronic systems.

Ferrite Isolator: The ferrite isolator is a dielectric-loaded, resonance-type, high-power device, designed to provide isolation of greater than 20 db and insertion loss of less than 0.5 db over the frequency range of 67.25 to 72.75 kMc. Oriented, barium-type ferrite materials are used. Rectangular slabs in rectangular guide are used for both the ferrite and dielectric loading material. It is interesting to note that the thickness of the "slab" is in the order of 0.006 inch. In order to achieve the required performance over the frequency range, a steel shunt of fixed size is required near the isolator magnet during operation at the upper portion of the frequency range.

The isolator and its performance characteristics are shown in Figs. 17 and 18. The isolator has been operated successfully at full magnetron power, nominally 10 kw.

[8] U. S. Army Signal Corps Contract No. DA 36-039 sc-73228, Cascade Res. Corp., Los Angeles, Calif.

Fig. 17—MM ferrite isolator.

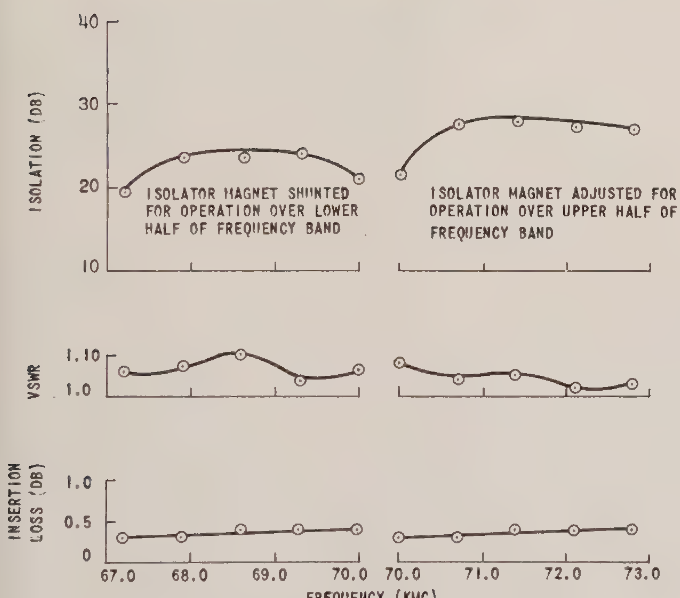

Fig. 18—Attenuator and VSWR as a function of frequency for ferrite isolator.

Ferrite Circulator: The ferrite circulator is a transverse-field, four-port, high-power device using 3-db short-slot hybrid couplers. The coupler design is essentially the same as that used in the balanced gas-discharge duplexer. Two 90° differential phase shifters and a 90° reciprocal dielectric phase-shift compensator are used. A schematic diagram depicting the circulator operation is shown in Fig. 19, and a photograph of the circulator is shown in Fig. 20. High saturation-magnetization nickel-zinc ferrites are used for the differential phase-shift sections. The reciprocal phase-shift compensator section consists of a pair of ceramic slabs mounted in the waveguide. A single permanent magnet supplies the magnetic field for both sides of the double waveguide section, since the small waveguide size prevents the use of individual magnets for each ferrite section.

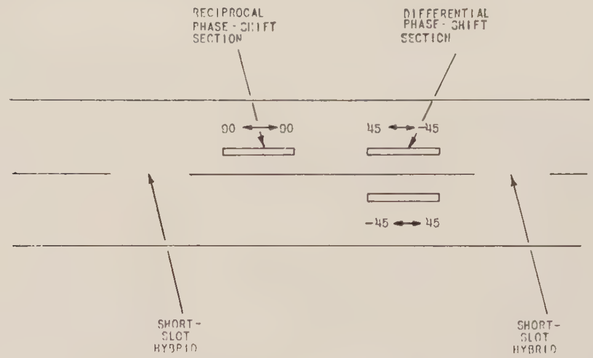

Fig. 19—Schematic diagram of circulator.

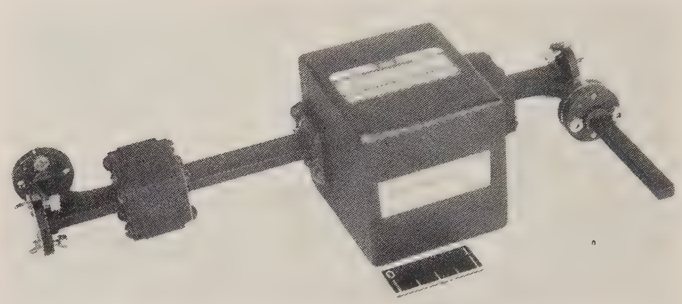

Fig. 20—MM ferrite circulator.

Typical performance characteristics for the circulator are shown in Fig. 21. It will be noted that the results achieved compare favorably with characteristics usually quoted for circulators operating at much lower frequencies. The device has been operated successfully with full magnetron power.

Ferrite Pulsed Attenuator: The pulsed attenuator is a low-power device, consisting of a cascaded pair of ±45° Faraday rotation sections. The polarization in the second section is rotated in a sense opposite to that of the first, providing parallel input and output polarization. Use of the two sections permits cross-polarized energy generated in the first section to be absorbed in the second. A cut-away sketch, Fig. 22, shows the design and operating principle of the pulsed attenuator. A photograph of the device is shown in Fig. 23.

"Fail-safe" operation is achieved by means of an external permanent magnet bias, which places the switch in a normally off condition. A pulsed current source can be used to turn on the device.

It was necessary to use silver-plated plastic waveguide in order to minimize the shorted-turn effect in metal waveguide walls, and to achieve fast switching.

Rise and fall times in the order of 1 μsec have been obtained for pulse repetition rates up to 50 kc. Typical performance characteristics over the frequency band are shown in Fig. 24.

Ferrite Switch: A three-port, low-power switch was designed to provide switching between one input port and two output ports. The design uses Faraday rota-

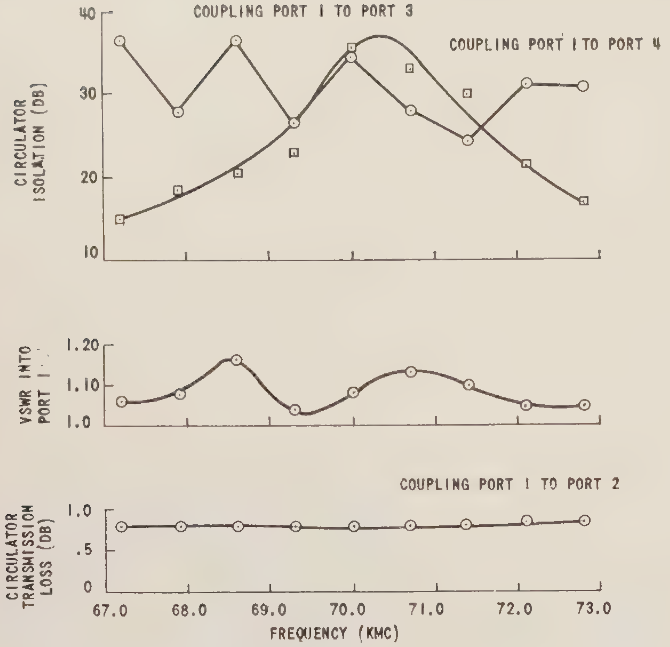

Fig. 21—Attenuation between ports and VSWR as a function of frequency for transverse-field circulator input at Port 1 only.

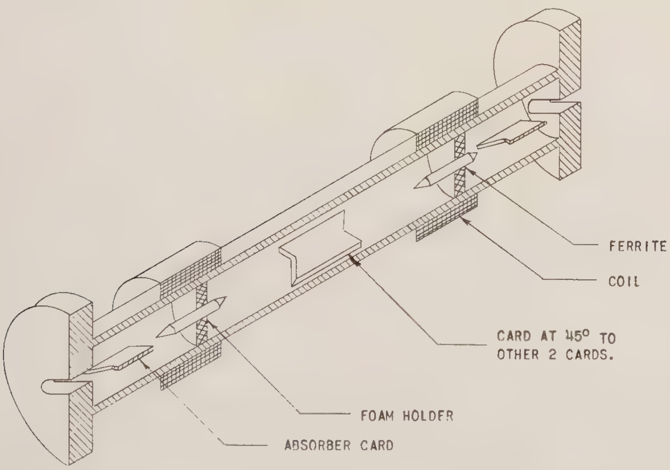

Fig. 22—Pulsed attenuator.

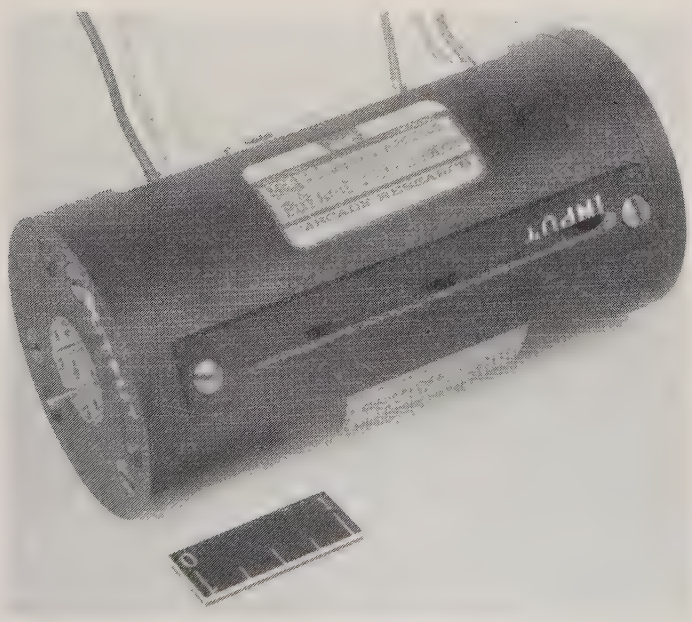

Fig. 23—MM ferrite pulsed attenuator.

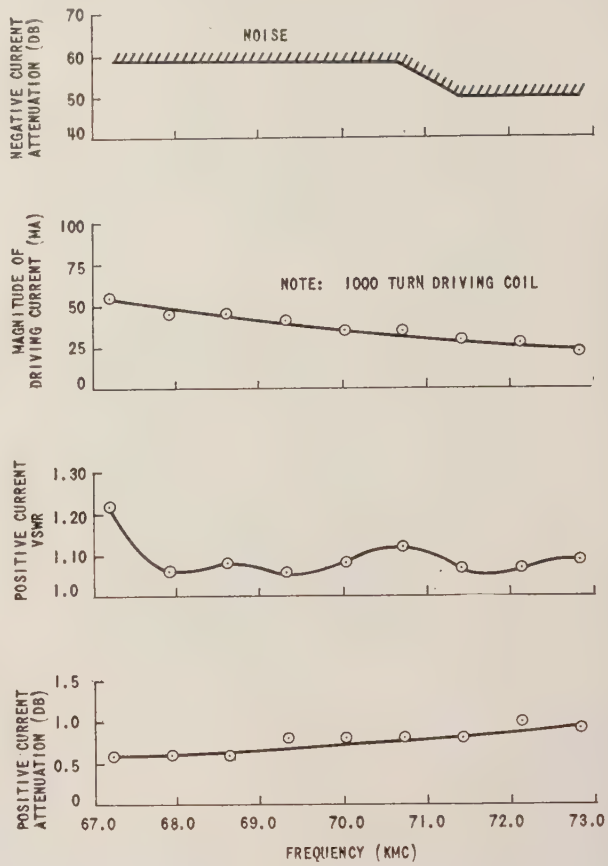

Fig. 24—Maximum and minimum attenuation, VSWR, and driving current as a function of frequency for pulsed attenuator, using Faraday rotation principle.

tion ferrite elements, in conjunction with 3-db hybrid couplers, and a longitudinal biasing field. With no biasing field and zero rotation, coupling occurs between Port 1 of the input hybrid and Port 2 of the output hybrid. When a longitudinal field is applied to both ferrite rotators in order to provide 90° of rotation, energy is reflected from each port of the output hybrid and is coupled out at Port 3 of the input hybrid. Thus the required switching action is provided. A schematic sketch of the switch (without hybrids) is shown in Fig. 25, and a photograph of the switch is shown in Fig. 26. Typical performance characteristics are given on the curves in Figs. 27 and 28.

Crystal Protector TR Tube: The development of the ferrite circulator pointed out the desirability of developing a low-power, gas-discharge crystal protector tube. A combination of the circulator and crystal protector would thus provide a complete duplexing function. Therefore, effort was devoted to the development of a crystal protector tube as one phase of the balanced duplexer program.[6]

Much of the design information and many of the fabrication and processing techniques accrued are directly applicable to both the low-power crystal protector tube and the high-power balanced dual TR tubes. However, the problems associated with optimum gas fill are different because of the difference in the incident power levels to which the two devices are subjected.

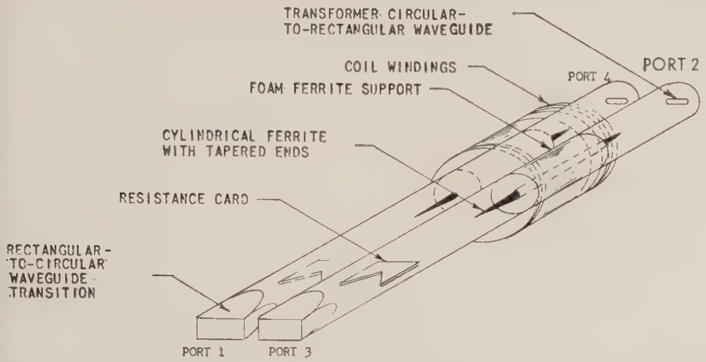

Fig. 25—Switching elements of millimeter ferrite switch.

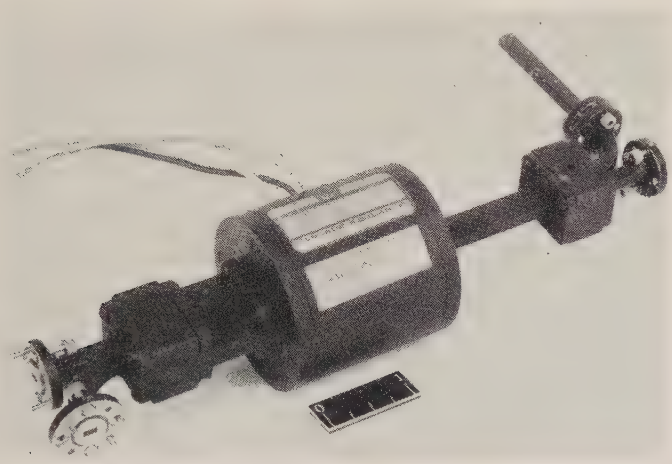

Fig. 26—MM ferrite switch.

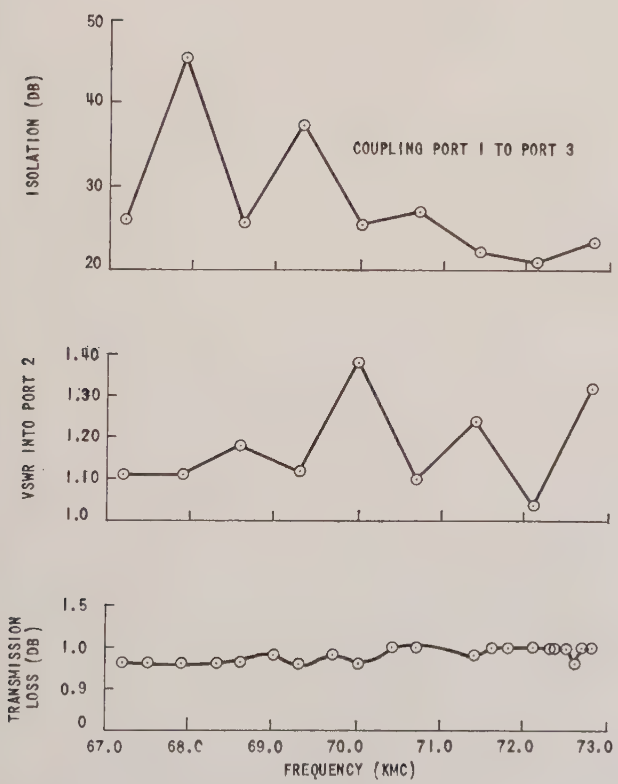

Fig. 27—Attenuator between ports and VSWR as a function of frequency; switching position 1 of reflection type three-port switch.

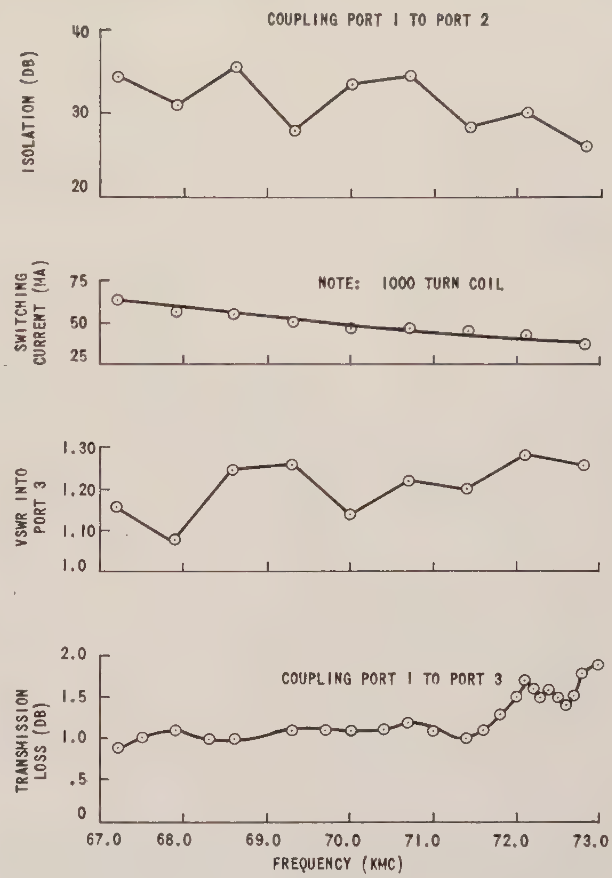

Fig. 28—Attenuation between ports, VSWR, and switching current as a function of frequency; switching position 2 of reflection type three-port switch.

An argon, xenon, and hydrogen mixture is used as the gas fill in the crystal protector tube. Both three-element and four-element crystal protector tubes have been designed. An assembly drawing of the three-element crystal protector tube is shown in Fig. 29, and a photograph of the tube is shown in Fig. 30. Typical low-level performance characteristics are shown by the curves of Fig. 31. High-power-level characteristics are as follows:

minimum firing power: 50-mw peak,
spike leakage at 100-watt peak: 0.36 erg,
flat leakage at 100-watt peak: 1.4 mw,
spike leakage at 3-kw peak: 0.32 erg,
flat leakage at 3-kw peak: 0.7 mw,
ignitor current: 100 μa,
ignitor voltage drop: 290 vdc,
recovery time: 3 μsec.

The development under the sponsorship and technical guidance of the Signal Corps of the gas-discharge and ferrite devices permits the system designer a wide freedom of choice in determining the optimum duplexing and switching configuration for his particular application.

The branched type of narrow-band, tunable, gas-discharge duplexer will probably have limited future use. Excellent duplexing performance can be obtained with the broad-band, balanced type of gas-discharge duplexer.

The ferrite isolator will eliminate the problems which

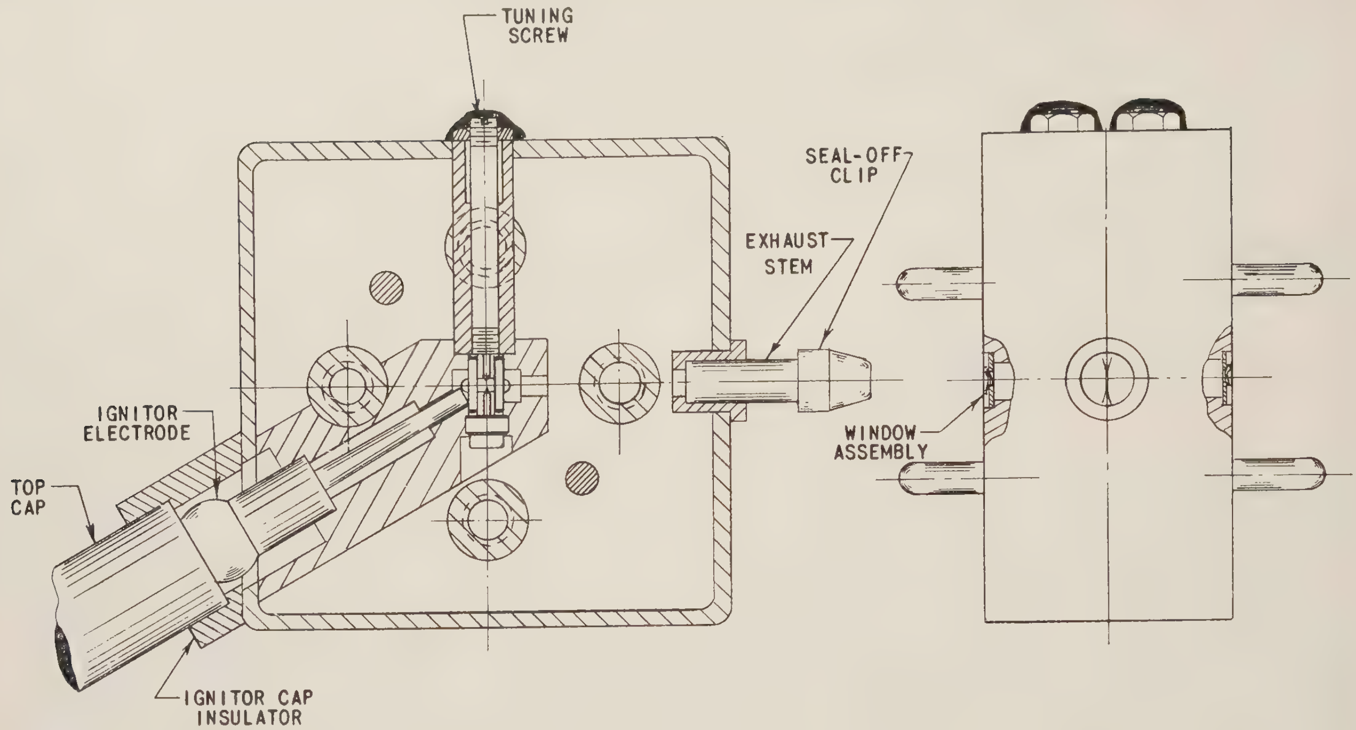

Fig. 29—Crystal protector tube assembly drawing.

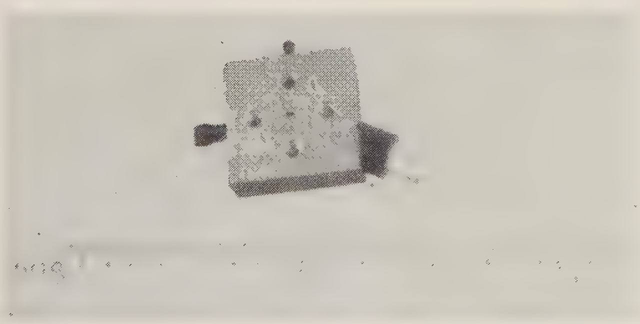

Fig. 30—Crystal protector tube.

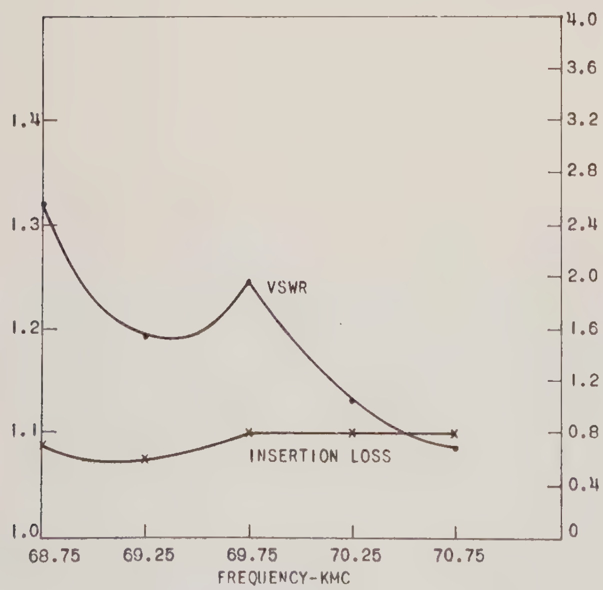

Fig. 31—MM crystal protector tube, typical characteristics VSWR and insertion loss.

arise because of high reflections being transmitted back to the magnetron.

A complete solid-state duplexer can be achieved by the use of the ferrite circulator and the pulsed ferrite attenuator. In this configuration, of course, it is necessary to pre-pulse the attenuator in synchronism with the transmitter.

The circulator and the crystal-protector-tube combination is another means of providing the duplexing function. In this approach, no pre-pulsing techniques are required.

The switch can serve as a low-level, three-port device. A combination of the isolator and the three-port switch provides a ready means for switching one high-power-level input port between two output ports.

Acknowledgment

The practical achievement of the operational millimeter devices described in this paper is the result of many years of effort. In addition to the authors, many individuals contributed substantially to various phases of the millimeter devices research and development programs through the years. Foremost among these are Arnold L. Winters and Beverly D. Kumpfer for the magnetron, Gerald I. Klein for the klystron, and John L. Carter for the gas-discharge and ferrite duplexing and switching devices. Measurements to determine the characteristics of the millimeter devices were made at USASRDL by Edward E. DeCamp, Jr., John J. Bruscella, and Robert M. Combs.

The authors request the indulgence of anyone whose participation and contribution to this program have been overlooked inadvertently.

Harmonic Generation by Means of Traveling-Wave Tubes*

F. E. KAVANAGH† AND K. WESTERMANN†

Summary—This paper describes the results of an experimental investigation conducted to determine the effectiveness of a traveling-wave tube used as a harmonic generator. It is shown that harmonics of a low frequency applied to one of the gun electrodes will be amplified by the helix and will appear at the output of the traveling-wave tube as a "picket fence" of RF signals. The paper describes the experimental techniques used and discusses the test results obtained. Among the parameters considered are carrier-to-noise ratio, uniformity of power output, and stability of the harmonics produced. Possible applications of a traveling-wave-tube harmonic generator are also discussed.

Introduction

One of the advantages of using a traveling-wave tube as a harmonic generator is that in this type of tube the harmonic frequencies generated can be derived from a quartz-crystal oscillator operating at a relatively low frequency, for example, around 50 Mc. Thus, high frequencies can be generated with quartz-crystal accuracy, normally one part in 10^5 or 10^6; and a useful multiplication of the fundamental frequency, in this case, up to the 33rd harmonic, can be achieved.

For harmonic generation of this type, no RF signal is applied at the input end of the helix. Instead, this end of the helix is terminated by a 50-ohm load, and the potential of one of the gun anodes in a multi-electrode gun is modulated so that the beam enters the helix with a high current modulation. Besides the modulation frequency the beam current contains many harmonics that have appreciable amplitudes, and only those harmonics lying within the pass band of the tube are amplified. Substantial amounts of harmonic power output may be obtained. The RF output of such a tube may be described as a "picket fence" of signals, each signal separated from its neighbor by an amount corresponding to the modulating frequency. This type of device lends itself to interesting system applications.

Description and Operation of Traveling-Wave Tube

A low-noise traveling-wave tube was used for the initial experiments because of its multi-electrode gun. However, any traveling-wave tube having a gun of this type could have been used.

In tubes designed for low-noise operation, the anode potentials of the electron gun are adjusted in such a way that the beam enters the helix at a noise minimum. The RF input signal is introduced in the vicinity of this beam noise minimum. For harmonic generation of the type under discussion, no RF input signal is applied at the input end of the helix, which is simply terminated by a 50-ohm load. The low frequency-modulating voltage is applied to one of the low potential anodes of the electron gun. For maximum harmonic generation, the beam current modulation produced must be high enough to insure that the amplitudes of the harmonics lying within the pass band of the traveling-wave tubes are as large as possible. In addition, for optimum harmonic power output, the gun anode voltages must be adjusted so that the maximum of the harmonic-frequency space-charge waves occurs at the input of the helix. The power output of the harmonics obtained was substantially higher than that anticipated.

It appears reasonable to assume that the first portion of the helix of a traveling-wave tube harmonic generator, into which a premodulated beam is injected, is more effective in producing gain than the first portion of the helix of a conventional traveling-wave tube, in which the RF signal is introduced at the RF input. In the case of the harmonic generator tube, the anode voltages are adjusted in such a way that the beam enters the helix with optimum modulation. This type of operation is different from that of conventional traveling-wave tubes, in which optimum modulation or bunching occurs farther down the helix. Unfortunately, when the various anode voltages are adjusted for maximum power output, the low-noise conditions in the gun are adversely affected. Nevertheless, the carrier-to-noise ratio was found to be in the order of 60 db, which is sufficient for most applications.

Experimental Procedure and Results

Maximum Power Output

A block diagram of the circuit used for the output power measurements is shown in Fig. 1. The modulation voltage was obtained from a signal generator whose maximum output was 2 volts at 76 Mc. A three-stage RF amplifier increased this signal to the 15-volt level, which was high enough to fully modulate the traveling-wave tube. The RF input end of the tube was terminated with a 50-ohm coaxial load. The power output of the harmonics was measured by means of a calibrated spectrum analyzer. To increase the accuracy of the measurements, a broad-band ferrite load isolator was used to match the traveling-wave tube to the spectrum analyzer.

The circuit of the traveling-wave tube used as a harmonic generator is shown in Fig. 2. As shown, the second anode of the tube is modulated. At the socket of the traveling-wave tube, the coaxial line coming from the 76-Mc amplifier is terminated with a resistance of 50 ohms. Direct-current isolation is provided by a 0.004-μf condenser. A 2-μf RF choke was inserted in

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

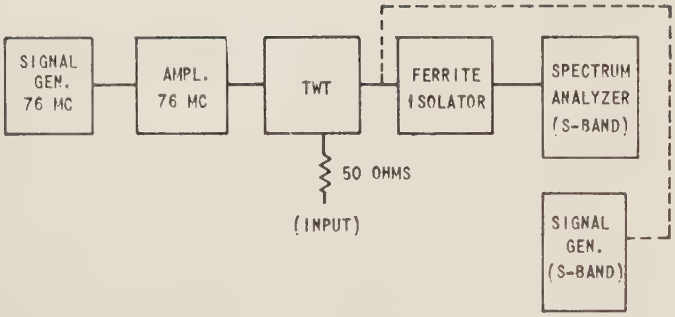

Fig. 1—Block diagram of test setup for power output measurements.

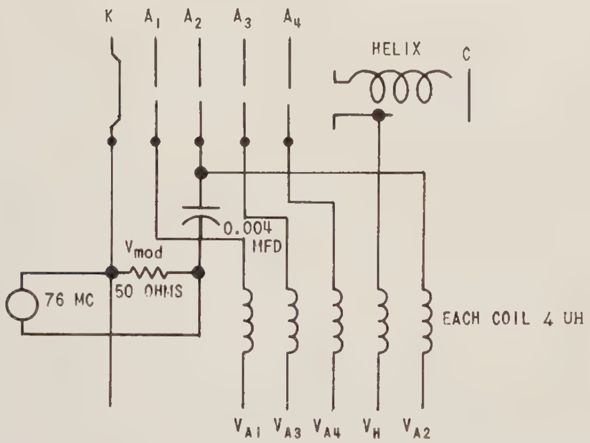

Fig. 2—Circuit diagram of traveling-wave tube used as harmonic generator.

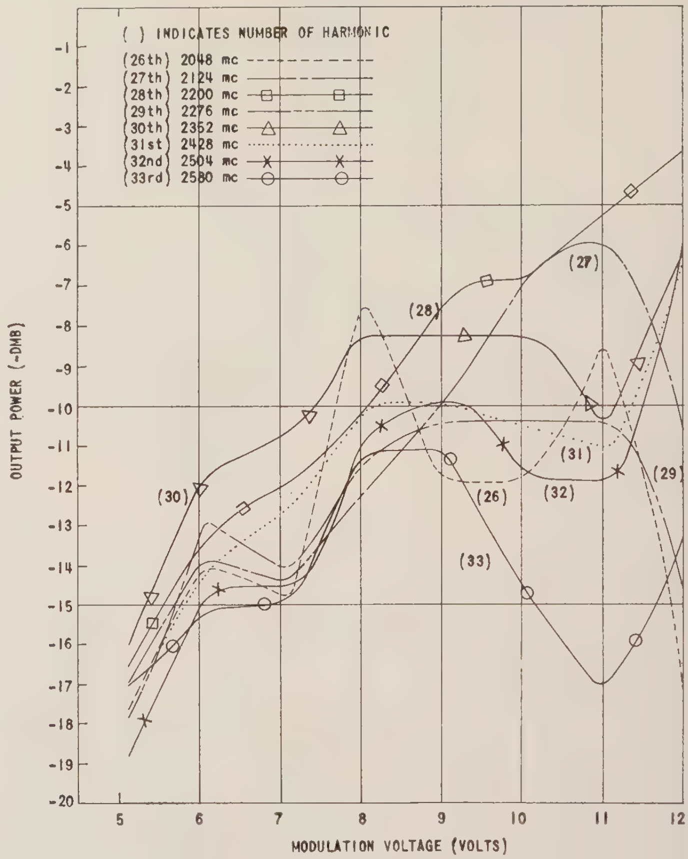

Fig. 3—Harmonic power output as a function of modulation voltage.

series with each of the other tube elements (except the cathode and collector) to prevent RF leakage into the dc power supply. The magnitude of the applied modulation voltage was measured at the socket terminals.

The power outputs of the various harmonics obtained by varying the modulation voltage are shown in Fig. 3. For each modulation voltage the various anode voltages and the helix voltage were adjusted for maximum power output for the 28th and 32nd harmonic (2200 and 2504 Mc). The power output of all other harmonics was also measured under this set of fixed conditions. Fig. 3 also shows that up to a modulation voltage of 8 volts the traveling-wave tube, when operated as a beam-modulated harmonic generator, can deliver in the order of 0.1 Mw at each of seven or eight harmonics. Under normal conditions, the tube delivers a saturated power output of 1 Mw. Harmonic power output increases with modulation voltage and does not vary from harmonic to harmonic by more than 4 db. If the modulation voltage is increased beyond 8 volts, selective overloading increases the power output of some of the harmonics and decreases the power output of others. Under certain high modulating voltage conditions, the power output of some harmonics becomes too small for practical use. Thus, for the particular tube used in these experiments, modulation voltages should be kept below 8 volts for satisfactory harmonic power output.

Saturation Characteristics

To investigate the tube's saturation characteristics under the described operating conditions, an additional 2500-Mc RF signal was applied to the input of the tube, and modulation voltage was simultaneously applied to Anode 2. At different modulation voltages the additional signal was slowly increased in strength until the amplitude of one of the harmonics, in this case the 28th, decreased slightly, which indicated that the tube was approaching saturation. As shown in Fig. 4, the power output of the generated harmonic and the amplified test signal were equal at 4 volts modulation; this point marked the onset of nonlinear effects. Fig. 3 shows these effects when the tube is operated in the saturated region.

Carrier-to-Noise Ratio

In order to determine whether or not the carrier-to-noise ratios of the various harmonics were high enough to permit use of the harmonic generator as a local oscillator in a microwave receiver, measurements were made of this important parameter as a function of modulation voltage. The method of measurement used is shown in Fig. 5. Since the noise power generated on both sides of each harmonic would be most detrimental to satisfactory operation of any receiver using the harmonic generator as the local oscillator, the spectral distribution of the noise power was of particular importance.

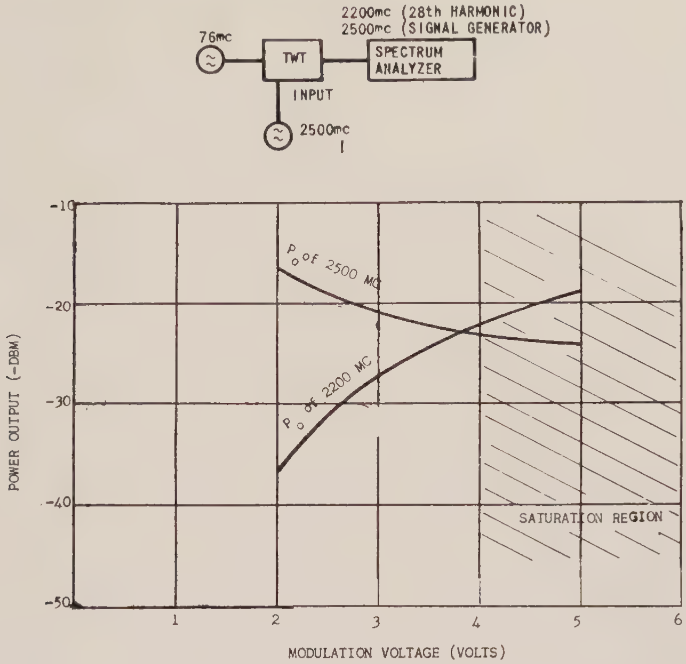

Fig. 4—Effect on harmonic signal as tube is driven into saturated region (for several modulation voltages).

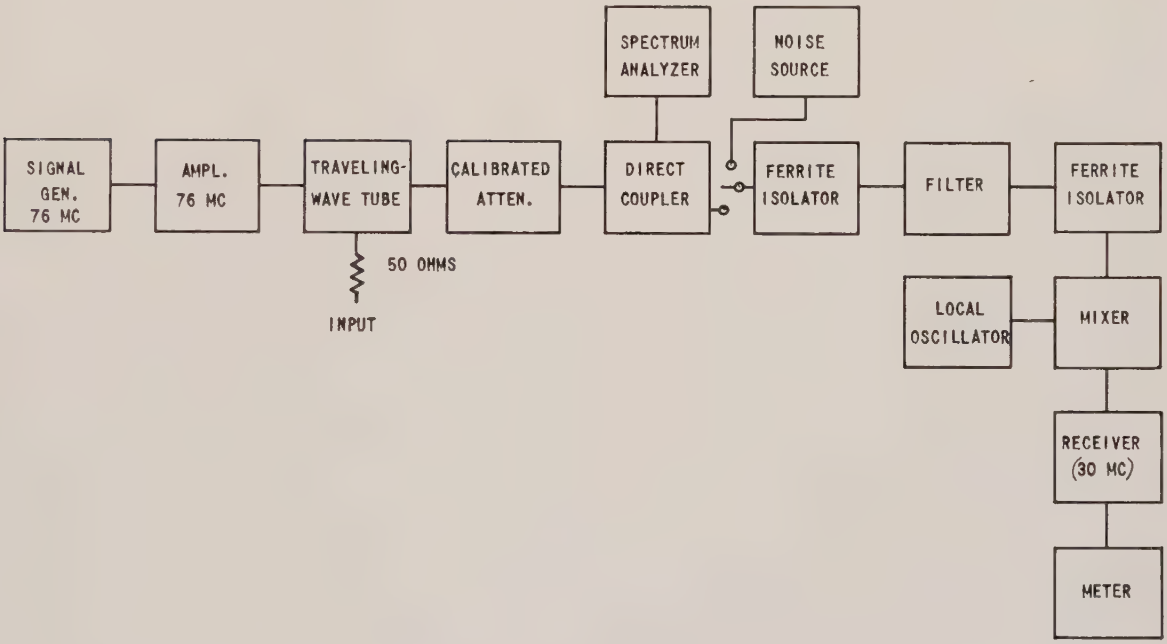

Fig. 5—Block diagram of test setup for noise measurements.

As shown in Fig. 5, harmonic power and noise power from the tube under test are passed through a calibrated attenuator and directional coupler to a filter and the mixer of a receiver. The ferrite isolators are used to match the filter input and output. The absolute power of the harmonics was measured by means of the spectrum analyzer connected to the directional coupler. The tunable band-pass filter has a carrier rejection of 65 db and a bandwidth of 3 Mc; the IF bandwidth of the test receiver is 1.8 Mc at an intermediate frequency of 30 Mc.

To measure the noise power 30 Mc away from one of the harmonic frequencies of the tube (f_H), the filter was tuned to (f_H+30) Mc, and the local oscillator of the test receiver was tuned to (f_H+60) Mc. The test receiver was calibrated by means of a noise source.

The noise measurements were made for three harmonics: the 26th (2048 Mc), the 28th (2200 Mc), and the 30th (2354 Mc). Fig. 6 shows a plot of harmonic and noise power output for different modulation voltages, and Fig. 7 shows the carrier-to-noise ratio of these three

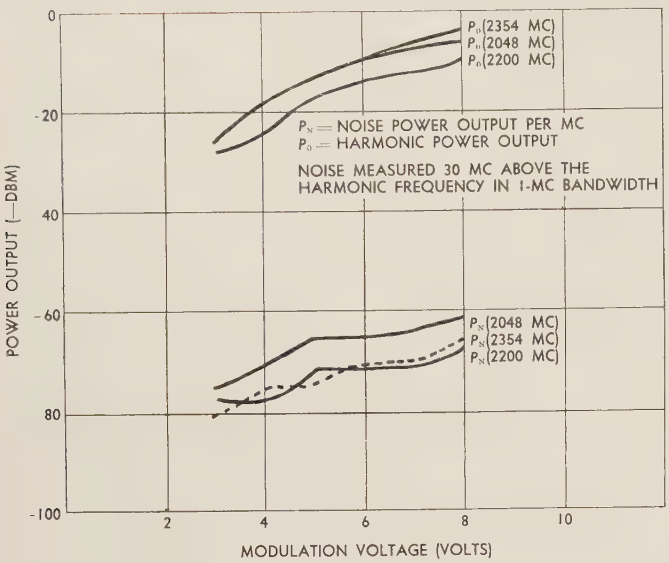

Fig. 6—Harmonic and noise power output as a function of modulation voltage.

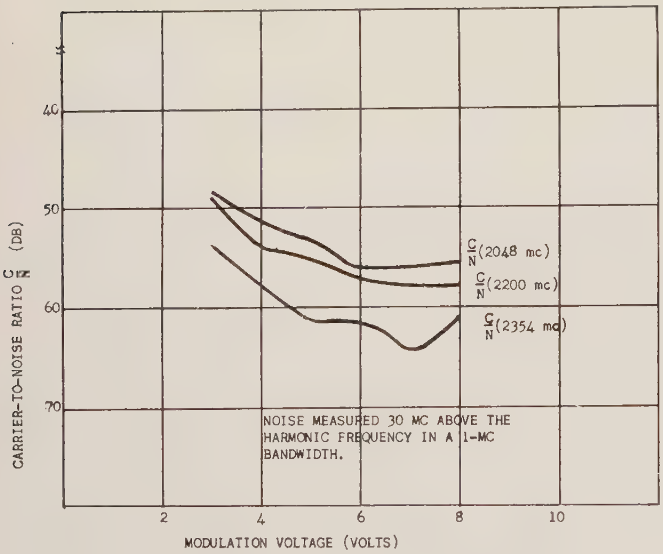

Fig. 7—Carrier-to-noise ratio for three harmonics as a function of modulation voltage.

harmonics. It can be seen from Figs. 6 and 7 that changes in carrier-to-noise ratio are due mainly to the variation in harmonic output power with modulation voltage. The carrier-to-noise ratio increases gradually as the modulation voltage is increased. Above 6 volts of modulation, the ratio remains nearly constant (of the order of 60 db), since from this point on, the noise output and power output increase at the same rate. The measurements show that the noise output of the traveling-wave tube, when operated as a harmonic generator, is relatively high. This high noise is due to the fact that for optimum harmonic power output the gun anode potentials were not, in general, the same set of potentials as those used to operate the tube as a conventional low-noise amplifier. Table I compares the operating conditions of the tube operating as a harmonic generator with those of the tube operating as a conventional low-noise amplifier. It is interesting to note that if the noise power output curves of Fig. 6 are extrapolated down to zero modulation voltage, the noise power would be of the order of -85 to -90 dbm/Mc, which corresponds to a noise figure of about 25 db, although the tube is capable of operating at a much lower noise figure when the gun potentials are properly adjusted for normal low-noise amplifier operation.

TABLE I

Comparison of Operating Conditions for Conventional Traveling-Wave Tube and Harmonic Generator Traveling-Wave Tube

Condition	Conventional Operation	Harmonic Generator Operation
I_m (amp)	1.6	1.6
V_f (v)	5.0	5.0
I_f (amp)	0.67	0.67
V_{A1} (v)	5.0	9.7
V_{A2} (v)	12.0	12.5
V_{A3} (v)	24.0	12.5
V_{A4} (v)	200	227
V_H (v)	390	375
I_H (microamp)	1	1
V_C (v)	400	400
I_C (microamp)	150	230
V_{Mod} (v)	—	8.0
f_{Mod} (Mc)	—	76

Applications

A harmonic generator of the type described has several interesting characteristics and application possibilities. For example, if the modulating voltage is derived from a conventional quartz-crystal oscillator having a frequency stability of one part in 10^6, the harmonics generated will all exhibit the same high stability. Unlike most harmonic generators, however, the traveling-wave tube generates a number of accurately spaced output signals which may be utilized individually or simultaneously as the driving signal in an amplifier chain. By following a harmonic generator with a narrow-band, electronically-tunable amplifier, such as a backward-wave amplifier, it is possible to frequency-code the output of a transmitter chain according to some prearranged program.

Conclusions

When the beam of a low-noise traveling-wave tube is modulated with a low-frequency RF signal, a large number of harmonics of the fundamental frequency are produced. Those lying within the pass band of the particular traveling-wave tube used will appear at the output of the tube at useful power levels.

The total harmonic power generated is roughly equal to the output power of the traveling-wave tube when operated in the conventional manner. Carrier-to-noise ratios in the experiments described were of the order of 60 db.

Advanced Power Sources for Communication Electronics*

DAVID LINDEN†

Summary—**Portable electrical power sources are being used in increasing numbers for a variety of applications on the ground and in outer space. The trend to miniaturization and transistorization has accelerated this practice.**

Chemical, nuclear, and solar energy are the three prime sources that are being used in power sources which will fulfill the new requirements. Each of these sources, in combination with new electrical conversion devices, has advantageous and unique characteristics which make it desirable for this application.

The characteristics of various types of recently developed electrical power sources are described and compared, and data are presented which illustrate the best operating conditions for each system.

Introduction

HIGHLY efficient portable electrical power sources are required in increasing numbers for a variety of applications both on the ground and in outer space. Transistorization, miniaturization, and other advances in electronics have served to accelerate this trend, and have resulted in the design of many electronic devices that heretofore were not practical. These equipments are dependent on the availability of compatible portable power sources for their successful operation. The development of such devices has been an important part of the research and development program of the Signal Corps.

The general requirements for portable power sources are that they be small in size and weight, rugged, noiseless, low in cost, and have a long, reliable maintenance-free life, being able to operate under all climatic and environmental conditions. Operation in outer space has added new environmental conditions, such as low gravity and pressure, temperature extremes from below −100°F to over 300°F, and exposure to high intensity radiation and meteorites. Power sources for missile use must meet the requirements of highly efficient operation at high discharge rates over short periods of time as well as extreme mechanical soundness to withstand the high shock and acceleration. New ground applications, particularly for military needs in remote areas and front line conditions, impose requirements such as operation under extremes of environment, no maintenance, and quiet operation, and low thermal output to make detection difficult. These trends have obsoleted many of the conventional portable power systems. New, more efficient systems are required for the "Space Age."

Chemical, solar, and nuclear energy are the three prime sources that are expected to fulfill these new power requirements. Each of these sources has certain characteristics which make it attractive. The chemical systems, for example, have the advantage of being a proven reliable source of energy with the highest power-to-weight ratio for short life operation. Chemical systems can be controlled to yield their energy when required and thus are excellent for the storage of energy. Nuclear energy provides the most concentrated compact source with operation that is generally independent of the temperature and not seriously limited in lifetime. Solar energy is attractive because it is free and inexhaustible and the life of the power source is not dependent on the quantity of fuel that is supplied.

A number of methods can be used for the conversion of these three sources of energy into electrical energy. The more important of these methods are summarized in Fig. 1. Of these, however, only two, the self-contained chemical battery and the rotating heat engine, such as the engine-generator, are in wide use today. New breakthroughs and advances that will come early in the Signal Corps' second centennial will make many new and superior power systems available for electrical power.

Chemical Systems

The Signal Corps has been pre-eminent in the development of chemical batteries. Despite the fact that they are over 100 years old, chemical batteries have many characteristics and advantages which cannot be equalled by other energy systems. Of course, continual progress has been made in the field, and modern batteries are only distant relations of their predecessors. Batteries are one of the best energy systems for short term applications, with proven performance and low cost. Their power-to-weight ratio is among the highest known. For this reason, they are used for secondary missile power and, in conjunction with other energy systems, for handling peak power requirements. The high-rate automatically-activated zinc-silver oxide battery, shown in Fig. 2, was developed by USASRDL, specifically for missile use. In the unactivated condition, it can be stored indefinitely in the missile, always ready for immediate use. It requires no maintenance or attention, but can be activated instantaneously to provide electrical power when required. Activation is accomplished by firing a gas-producing squib which forces the electrolyte into the battery cells. This activation is accomplished in less than one second.

The magnesium battery, another recent Signal Corps development, is an important step towards fulfilling the need for a long-life, nonperishable, portable power source. As shown in Fig. 3, the magnesium battery has about twice the capacity of the conventional zinc battery, and a storage life of better than four years. With

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

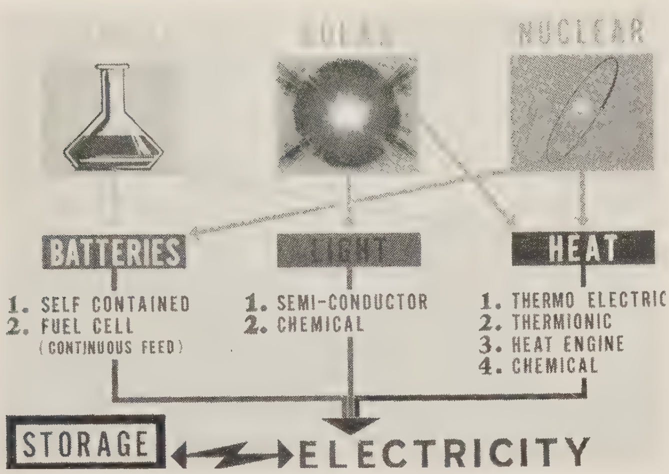

Fig. 1—Energy systems.

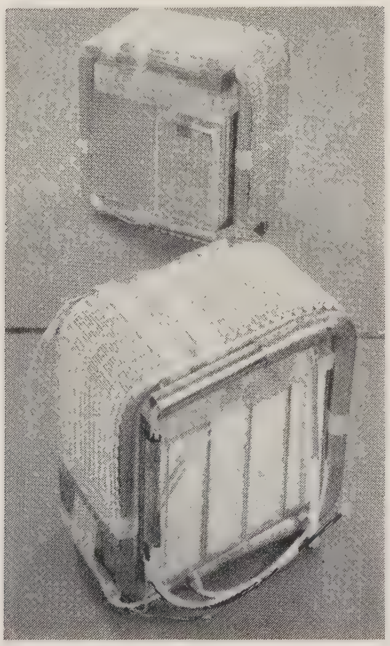

Fig. 2—Automatically activated zinc-silver oxide battery BA-472()/U (standard). Power supply for guidance section of Nike Hercules Missile, over-all 3/4 view. Showing (front) electrolyte trap and vent tube with relief valve assembly, copper tube electrolyte reservoir, gas generator, diaphragm adapters, woven wire heaters, 80°F, 115°F, and 145°F thermostats, and (rear—reflected by mirrors) unit cell constructed battery and 90°F monitor thermostat.

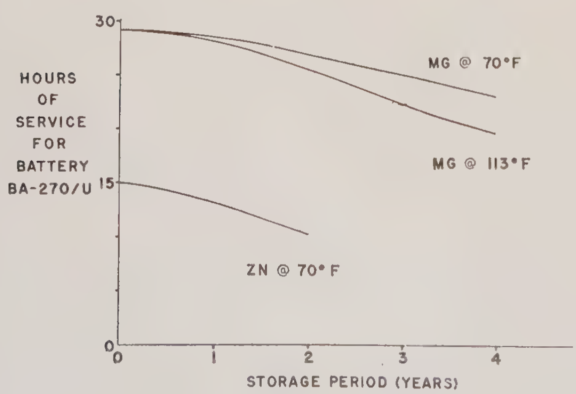

Fig. 3—Capacity and storage characteristics of the magnesium battery.

organic depolarizers, it is anticipated that new research will lead to the development of dry batteries with an additional 100 per cent increase in performance.

Chemical storage batteries are, at present, the most practical method for energy storage, with the nickel-cadmium battery, because of its high cycle life, being the most outstanding. Investigations of the zinc-silver oxide and cadmium-silver oxide systems to increase the energy/weight ratio and to improve reliability and cycle life should result in the development of storage batteries with at least a 2- to 4-fold improvement from the present 10 to 12 watt-hours per pound. The nickel-cadmium battery has already demonstrated its capability in missiles, in communication equipment, and in several of the satellites launched by the United States and the Soviet Union. Many new uses will be made of rechargeable batteries, particularly in the sealed version.

The fuel cell or continuously fed battery is another method for converting chemical energy into electricity. The operation of a fuel cell is similar to the battery, as shown in Fig. 4. The fuel and oxidant are fed into the cell

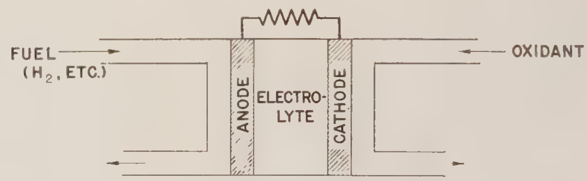

Fig. 4—Fuel cell battery.

on demand and an electrochemical reaction produces electricity. Fuel cells are becoming very attractive as a power source because of their many advantages. The intermediate step of conversion to heat that is necessary with Carnot cycle devices is eliminated, thus offering the possibility of over-all fuel conversion efficiencies in the order of 70 per cent. No moving parts are required, except for auxiliary functions. This results in quiet operation, long life, and a minimum of maintenance. Many of the fuel cell systems have a relatively low operating temparature, making infrared detection difficult. Most cells, and there are many types, now operate on hydrogen-type fuel with air or oxygen as the oxidant. Eventually, the fuel cell should operate with a variety of fuels, such as gasoline or kerosene. Practical cells with 150 to 800 watt-hours per pound should be available within two to five years. A mock-up of a man-pack fuel cell envisioned for silent operation of forward area portable communication and surveillance equipments is shown in Fig. 5.

Another type of fuel cell is the regenerative one, in which the fuel and oxidant necessary to operate the galvanic system are regenerated from the cell reaction products from an external energy source (solar, thermal, nuclear, etc). The regeneration process may be carried out by electrolytic, thermal, photochemical, and radiochemical methods.

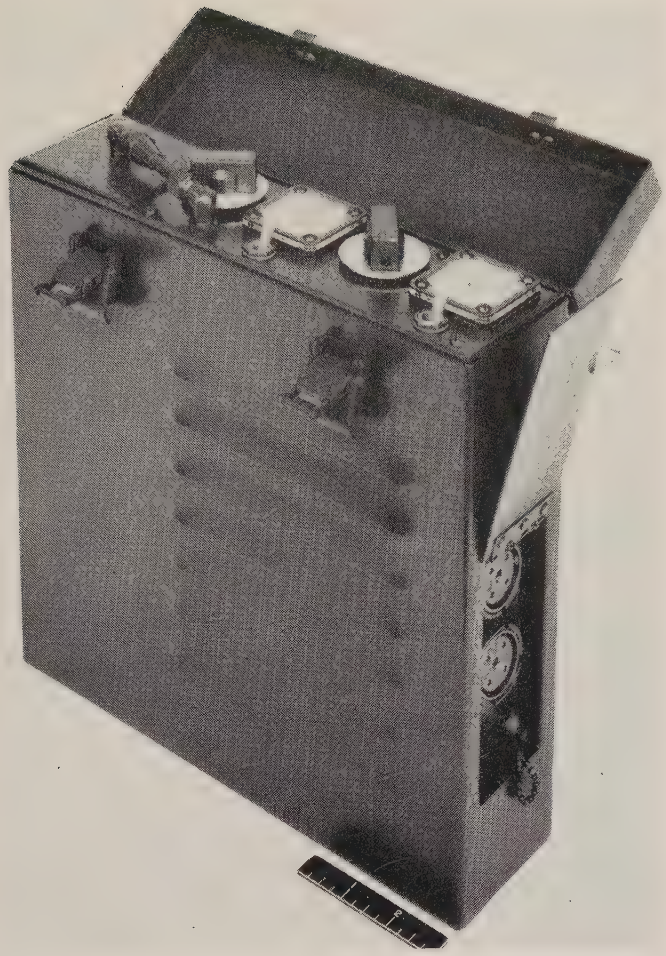

Fig. 5.

Solar Energy

Solar energy is important because it is a free, continuous, and inexhaustible source of energy that is available "for the taking." The energy-to-weight ratio of a solar energy power source can become quite high, especially if it is used for a long period, as its life is limited only by the converting device and not by the availability of a "fuel." Solar energy reaching the earth each year amounts to 3×10^{21} BTU under conditions of full sunlight at the earth's surface. This is equivalent to 1000 w/m^2. Above the earth's atmosphere, the radiation is equal to about 1400 w/m^2; at Venus, 2650 w/m^2; and at Mars, 600 w/m^2.

The most satisfactory and simplest means for converting solar energy into electrical energy at the present time is the silicon solar cell. This solid-state converter has no moving parts, and, since nothing is consumed or destroyed during the conversion process, this solar battery should have a long reliable operating life. It has been used successfully in a number of satellites and ground applications. The power source in Vanguard I, designed and fabricated at USASRDL, was the first demonstration of a solar cell as a practical source of power for space application. March 17, 1960 marked the second year of continuous, undiminished power generation by this device.

The development of the silicon solar cell has now reached the point where a conversion efficiency of about 10 to 11 per cent has been attained on a production basis with small, two-square centimeter cells. Thus, at full sunlight at the earth's surface, the output of a solar cell is about 10 to 11 mw/cm^2 and about 40 w/lb. However, the full output power is not realized in most cases because of a number of degrading factors. Correcting for these features, the cell output power is reduced to 8 mw/cm and 2 w/lb. Forecasted for the future is an inexpensive blanket type converter, such as the one illustrated in Fig. 6, which can be folded compactly into a small, easily handled package and opened and exposed to the sun when electrical power is required. It is conceivable that up to 100 watts of electrical power can be obtained with a square yard of thin sheet type solar converter when these new large area materials are developed.

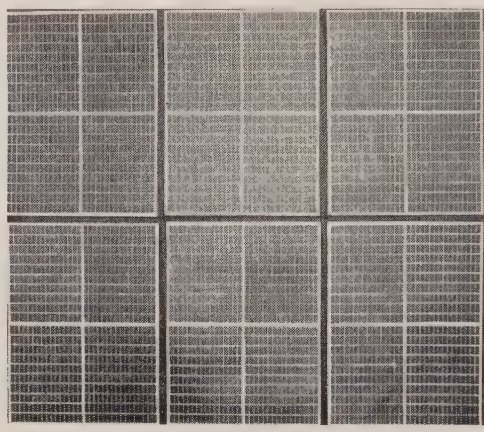

Fig. 6.

Light energy can be converted to electricity by other methods under investigation. With a photo-emissive diode, it has been indicated that conversion efficiencies of about 1 per cent and a very desirable power-to-weight ratio of 50 w/lb is possible. A three-fold improvement appears quite feasible with further development.

Another example is the photogalvanic device which converts solar to electrical energy by electrochemical means. A typical system utilizes a photosensitive metal oxide or metal halide which under radiation would be converted to the metal and the related oxidant. These two materials form the anode and cathode of the battery and will deliver electrical energy when they are reconverted electrochemically to the original material. These devices are still in the research phase, and conversion efficiencies, reported to date, are less than 1 per cent, but it is not unreasonable to expect a conversion efficiency as high as 40 per cent when this system is fully developed. The photogalvanic devices have an advantage as they contain their own built-in storage devices. The battery, once charged by solar radiation, can be discharged at will, and not only during periods of radiation as is the case with the photovoltaic devices. Another advantage is that the rate at which the battery can be discharged is not limited by the level of radiation, but by the battery design.

Nuclear Energy Systems

Nuclear energy systems provide a source of electrical energy in the most concentrated, compact form, capable of yielding over 1000 times the energy in a given weight than the chemical sources. Their performance is generally independent of the ambient temperature and other external influences. On the negative side, nuclear power sources have the disadvantage of radiating continuously or being difficult to "shut off." The full energy capabilities of the system, thus, are not realized unless the power source is used continuously and at full output. Nuclear sources also create a secondary environment of nuclear and thermal radiation which requires heavy shielding and a means of dissipation of the waste heat.

Nuclear power sources can be classified into two types: those using the energy released in the decay of radioactive isotopes, and those employing a reactor source.

The power output of a nuclear reactor is relatively constant and its thermal energy can be converted to electrical energy by a heat engine. These units are not efficient, from a power-to-weight ratio, in sizes smaller than about 3 kw.

The power of a radioisotope is determined by its decay characteristics, *i.e.*, the rate of decay and the energy per decay. This power output decreases exponentially with increasing time and falls off to one-half of the original output in a period of a half-lifetime. Radioisotope sources are limited to low power levels and special applications because of the dangers inherent with large concentrations of material.

Thermal Energy Conversion

Two important thermal energy conversion devices are the thermoelectric and thermionic converters illustrated in Fig. 7. These are solid-state devices, involving no moving parts, and consequently they should be long-lived, reliable, quiet, and require a minimum of maintenance. Thermoelectric generators, using conventional and nuclear heat sources, have been successfully demonstrated during the past two years with an over-all efficiency of about 5 per cent. They are now in the advanced development stage for ground and satellite applications. Even more promising is the thermionic converter. This is basically a diode which converts thermal energy to electricity through the principle of the Edison effect. It contains two electrodes, one of which is heated to a temperature that causes electrons to boil off its surface. The other is a cold electrode, which captures these electrons, thus causing a flow of electric current. Technologically, the thermionic converter is not as advanced as the thermoelectric generator; however, its conversion efficiency should be considerably higher than the thermoelectric generator because of its higher temperature of operation. Even higher total system efficiencies are possible by combining these two devices and using the rejected heat of the thermicnic converter for the hot junction of the thermoelectric generator.

An engineering concept of a thermionic converter, using solar energy as the heat source powering a remote radio relay or automatic weather station is shown in Fig. 8. An assembly of thermionic converters, mounted in suitable solar energy concentrators, can be used on an orientation pedestal to provide power for a satellite. The large insert shows how the reflector is used to concentrate the sun's energy and then pass it on to the thermionic converter. This device will require a minimum of maintenance and can provide around-the-clock operation with a suitable storage device.

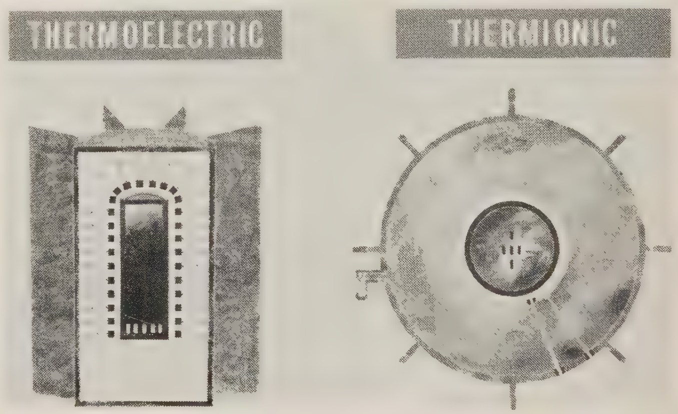

Fig. 7 Nuclear-thermo systems.

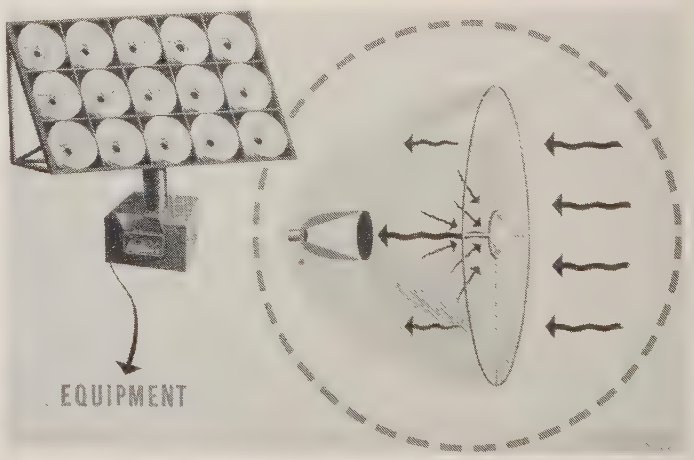

Fig. 8—Solar thermionic energy source.

Energy Storage

An important element of any electrical power system is the energy storage device. This component is needed because, generally, the prime source of energy is not available at the proper power level when required. Solar energy, for example, is not available during periods of darkness. Nuclear energy, on the other hand, is available continuously in most systems, and, to avoid waste, should be stored for future use during periods when electrical energy is not needed.

There are many ways of storing energy. Energy can be stored as heat in various forms, but none of the methods is efficient, since the storage device imposes a severe weight and volume penalty. Even with extremely good insulation, the energy will be dissipated gradually. Energy can also be stored mechanically, using very reliable methods such as flywheels, springs, and compressed gases and liquids. However, they too are limited because of their high weight-to-energy ratio. Energy can also be stored for long periods by exciting solid crystals with X rays, gamma rays, and other such radiation. This new approach is extremely interesting, although at present, its weight-to-energy ratio is very high, and its efficiency is low.

Chemical storage of energy in batteries appears to be the most satisfactory and practical method now available. But, at best, these and similar electrochemical storage devices do not have the desired high energy-to-weight and volume ratio nor the required life.

Storage in the form of bulk chemicals may ultimately be the most effective means for energy storage. The chemical compounds can be derived from the prime source of energy by a number of methods, for example, dissociation by thermal energy, dissociation by electrolysis, nucleo and photogalvanic effects. This storage is not encumbered with the physical limitations or limited life of other methods, although a means of containing the chemicals during storage and for converting them later to electricity is required. The regenerative fuel cell and photogalvanic systems are two examples of such storage systems.

Electrical-to-Electrical Conversion

Electronic equipment requires electrical power at specific voltages and currents, ac or dc, with varying degrees of regulation and control, to perform their necessary functions. These specific outputs are provided from the prime power source by means of an electrical-to-electrical converter.

The transistorized power converter, due to its high efficiency, low weight, small volume, and inherent reliability, has been able to fulfill the needs until now. Its limitations with respect to operating temperature, magnitude of voltage and current, power dissipation and radiation resistance will have to be studied in the attempt to improve the dynamic characteristics of the transistorized converter if it is to meet the stringent future requirements.

Considerable improvement is envisaged by the application of silicon controlled rectifiers, or silicon power transistors, which will increase the upper operating temperature limit. The silicon-controlled rectifier will also enable the converter to operate at higher switching frequencies with higher power ratings, thus permitting greater miniaturization and weight reduction. Investigation of nondissipative regulating systems will result in reduction of heat generation of the converter with consequent improvement in efficiency.

Conclusion

Many new types of electrical power sources will be available to power the electronic equipment of the "Space Age." Some of these power sources now are available for practical applications; others are approaching the final stage of development. There will be no universal power source to satisfy our present and anticipated requirement. Each energy system has specific advantages and will have its place in the over-all picture. Fig. 9, for example, shows the areas in which each of the three prime sources of energy predominate. The chemical systems are superior for applications which require operation for only relatively short periods of time. As the service life is increased, they become excessively heavy and bulky compared to the other energy sources. The chemical systems also can be used in low power applications and are outstanding for short-term high rate discharge. Solar energy systems show up most favorably in applications requiring long life operation at low and moderate power levels, but large collection areas are needed because of the low energy densities. For the high-power, long-life requirements, the nuclear reactor systems appear to be the most promising if the problems of radiation hazards can be successfully overcome.

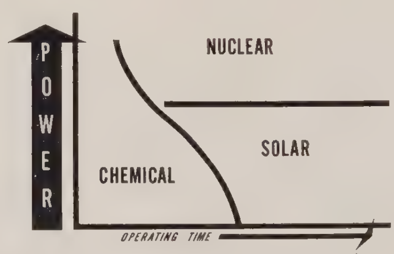

Fig. 9—Electrical power sources.

Acknowledgment

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Two Decades of U. S. Army Mobile High-Frequency Communications*

H. C. HAWKINS†

Summary—This paper is an historical account of the trend in development of U. S. Army high-frequency mobile radio communications of medium power in the period 1940 to 1960. Starting with one of the first really mobile sets of this power level, in a wide variety of installation configurations to meet World War II requirements, it relates the progressive fulfillment of higher traffic handling capabilities in both single and multivehicle installations. The increasing demand for smaller but higher capacity equipments indicates the course which future development efforts should follow.

THE development trend in medium-power high-frequency mobile radio communications sets for U. S. military use over the past two decades can be considered more of an evolution process rather than a break-through. The evolution can best be followed by a chronological account of the efforts made to improve the communications capability of these sets.

The first military medium-powered high-frequency communications set with a measure of mobility was Radio Set SCR-197, which made its appearance in the late thirties. This set covered a frequency range of 1.5 to 18.0 Mc, and had an output power of 400 watts A1 emission (telegraphy by means of on-off keying of the radio frequency carrier) but with grid modulation, A3 emission (telephony by means of double sideband, full carrier, amplitude modulation) was limited to about 75 watts output. It was not a truly mobile set since it could operate only when stationary. Two van-type vehicles, whose maneuverability left something to be desired, housed the radio and power equipment.

Inspired by the results of the Louisiana maneuvers of 1940 and the blitz type of warfare then underway in Europe, military characteristics were written for a radio set with a high degree of mobility and the capability of providing voice communication over a 100-mile range while in motion.

The Signal Corps Laboratory undertook the development of such a set. The commercial field was searched for a suitable transmitter having the compactness and potentialities required for the desired installation. Several types were purchased from different manufacturers and given thorough road and range tests.

The transmitter selected was the Hallicrafters HT-4 which later, after modification, became known as Radio Transmitter BC-610.

This transmitter, together with then standard military communications receivers BC-312 and BC-342, were assembled in a one and one-half ton four wheel drive panel truck. This truck towed a one-ton cargo trailer which contained a five-kilowatt engine-driven generator for station power. This set, pictured in Fig. 1, became known as Radio Set SCR-299. The transmitter provided 400 watts A1 and 325 watts A3 operation over the frequency range of 2.0 to 8.0 Mc.

The receiving equipment covered the frequency range of 1.5 to 18.0 Mc in six bands. Both the BC-312 and the BC-342 were single conversion superheterodyne receivers capable of receiving telegraph and voice modulated signals. Radio Receiver BC-342 operated from a power source of 115 volts ac, whereas Radio Receiver BC-312 operated from a power source of 12 volts dc.

Service test of the SCR-299 showed that this set was not considered satisfactory in all respects since it did not meet all the requirements stated in the military characteristics and lacked the high degree of mobility required. However, it was approved for training purposes until a more completely suitable unit became available and was obtainable. Procurement of a limited number was made.

Shortly therafter the United States became a combatant in World War II. The urgent need for the type of communications afforded by the SCR-299 made it necessary that some of its other shortcomings be tolerated, so large numbers of this set were procured and shipped to various combat zones.

In the meantime, the Signal Corps Laboratory was making an intense effort to improve the equipment in respect to both mobility and form factor. The distinctive appearance of the SCR-299 had proved to be an immediate invitation to particular attention by enemy aircraft.

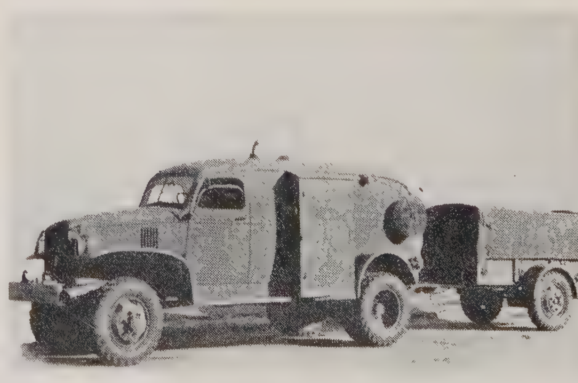

Fig. 1—Radio Set SCR-299.

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

In order to disguise the radio set and at the same time improve mobility, it was decided to install the equipment in a slip-in type of shelter which could be carried by a two and one-half ton 6×6 cargo vehicle. The shelter was designed to have the shape of the covered cargo area of the vehicle and, when the truck's tarpaulin was in place, it could not be distinguished at a distance from any other cargo truck. The two and one-half ton 6×6 truck provided increased mobility over the one and one-half ton 4×4 vehicle. Moreover, the removable shelter would allow use of the truck when the radio set could be placed on the ground and operated in a fixed location.

No improvement of great significance was made in the communications effectiveness, except that the frequency range of the transmitter was increased to cover the range of 2.0 to 18.0 Mc. Different mounting arrangements were made for the receivers and control equipment so that all components of the radio set could be removed and set up for operation without the shelter.

The basic set, shown in Fig. 2, received the nomenclature Radio Set SCR-399 in 1943. The same set, without the shelter and without a trailer for the power unit, was called Radio Set SCR-499. This set afforded a flexibility of mounting arrangements which permitted installations in a variety of vehicles, including the armored half-track personnel carrier, the amphibious "Duck," Cargo Glider CG-4A, and some components of the set were even installed in the quarter-ton 4×4 "Jeep" for use by airborne units.

While the SCR-399 and SCR-499 did contribute to a large degree to successful communications and continued in use long after the war, there was also a need stated for a set with greater capabilities both as to traffic handling and power output. The design of a high-speed CW telegraph set with a power output of two kilowatts was undertaken.

This set, designated Radio Set AN/MRC-1, required the development of a two-kilowatt radio frequency amplifier which was designed and fabricated at the Signal Corps Laboratory. Components of Radio Set SCR-399 and Boehme high-speed telegraph equipment were assembled into a complete operating station having a frequency range of 2.0 to 18.0 Mc for transmission, and 1.5 to 18.0 Mc for reception.

Using the same type of shelter as in the SCR-399, the high-speed telegraph station required two HO-17's, one for the transmitting equipment and one for the receiving and control equipment. Two two-and one-half ton 6×6 cargo vehicles were used to transport the equipment, each of which towed a one-ton cargo trailer containing Power Unit PE-95.

The transmission capability of this set was several hundreds of words per minute, but the actual amount of traffic which could be handled was limited by the proficiency of the operators in preparing perforated tape for transmission as well as reading and transcribing the received inked tape.

About thirty Radio Sets AN/MRC-1 were delivered to various theaters of operation before the end of any hostilities in World War II.

Before the completion of Radio Set AN/MRC-1, investigation was undertaken in the Signal Corps Laboratory to determine the most effective means of incorporating a facility for radioteletype in a set of the AN/MRC-1 type. The results of the investigation indicated that the frequency shift method of radioteletype transmission could readily be adapted to this set, so the equipment design was immediately started.

Components of Radio Set AN/MRC-1, with an improvement in the two-kilowatt radio frequency amplifier, were used with Radioteletype Equipment AN/TRA-7, which was designed and built specifically for this application, to form Radio Set AN/MRC-2. This set provided a single 60-word per minute channel of radioteletype in the same frequency range and power level as Radio Set AN/MRC-1 which it ultimately replaced. Three shelters of the HO-17 type house the transmitting set, the receiving set, and the operating center, as pictured in Fig. 3.

Radio Set AN/MRC-2 was scheduled for use in the planned invasion of Japan in 1945, and a number of sets were shipped to some Pacific islands and put in operation before V-J day.

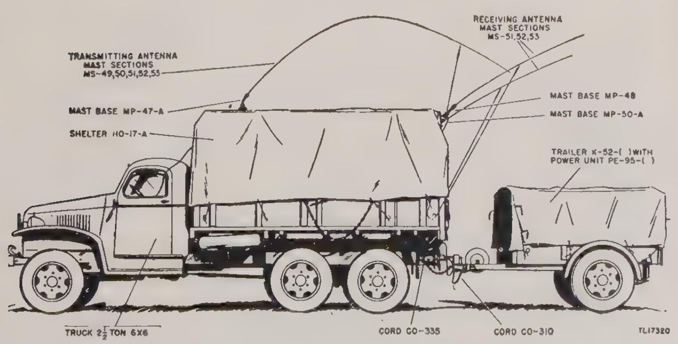

Fig. 2—Radio Set SCR-399A, installed as a mobile station.

Fig. 3—Radio Set AN/MRC-2.

The facility afforded by the availability of Radioteletype Equipment AN/TRA-7 made possible the installation of a frequency shift radioteletype service in the Presidential train in the fall of 1945. Later, in the spring of 1946, a radioteletype set employing modified components of the AN/TRA-7 was installed in the Presidential plane. This is believed to have been the first time that frequency shift radioteletype was employed in an airborne installation.

Shortly after the war, effort was concentrated on improving the communications effectiveness of the so-called "100-mile" sets, SCR-299 and SCR-399. The radioteletype facility provided by the AN/MRC-2 was then considered a logical choice, so a redesign of the SCR-399 was undertaken to provide a single vehicle radioteletype set. In accomplishing this, the AN/TRA-7 equipment was used as in the AN/MRC-2. The new design provided all the facilities of Radio Set AN/MRC-2 with the exception that there was a reduction of power from two kilowatts to four hundred watts. Notwithstanding, successful communication was obtained over distances of up to 1000 miles during tests. A new design of shelter to house the equipment, together with a rearrangement of set components, provided greater operator comfort and increased operating efficiency. This mobile radioteletype station is called Radio Set AN/GRC-26, and is shown in Fig. 4.

Several changes have been made in Radio Set AN/GRC-26 since the basic set was first built. Different letters of issue were assigned for each of the various steps representing improvements in the equipment. In the current model, AN/GRC-26D, are found some of the results of development effort since the end of World War II. These include Radio Transmitter T-368/URT, Radio Receiver R-390/URR, Frequency Shift Converter CV-116/URR and Modulator MD-239/GR, which have replaced older items of lesser reliability and efficiency.

For applications where teletype operation is not necessary, the basic functions of Radio Set SCR-399 are preserved in Radio Set AN/GRC-41. This set is used principally by the Air Force for ground-to-air communication. As in the AN/GRC-26D, which it resembles in outward appearance, the older communications equipments, such as the BC-610 transmitter and BC-342 receiver, have been replaced by the newer equipment developments. The shelter offers the same degree of comfort and operating convenience as is found in the teletype set.

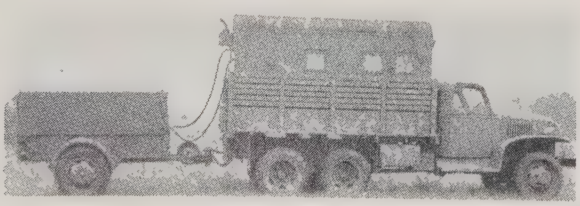

Fig. 4—Radio Set AN/GRC-26 (standardized). Curbside view of complete assembly, showing equipment as installed on vehicle ($2\frac{1}{2}$ ton); with antennas down, windows and hatch closed, it is prepared for operation.

The sudden demands of limited war and brush-fire combat which have been a threat since the end of World War II imposed mobile communications requirements which the sets previously described were not capable of fulfilling. The type of set needed was one of high traffic capacity which could be air transported and landed in the area of activity. A multichannel teletype facility was required which could handle the expected volume of traffic and also be capable of working into the Army Command and Administrative Network.

Two different sets were built initially, in an effort to satisfy these requirements. One, Communications Central AN/GRC-98, provided a four-channel frequency shift time division multiplex system. The other, Communications Central AN/TSC-16, was a single sideband set with greater traffic capacity.

The first of these sets was hastily assembled of parts available in depot stock or readily available from commercial sources. It used transmitting components of the old AN/MRC-2 with Telegraph Terminal Set AN/FGC-5 for time division multiplex. The second, AN/TSC-16, was built under contract on an expedited basis. It employed, among other items, a ten-kilowatt single sideband transmitter which, with a tone teletype terminal for frequency division multiplex, provided sixteen teletype and two voice channels. The physical size and weight of both of these sets are excessive for the type of operation intended, since loading in aircraft and landing at a required location are handicapped by both.

A more recent assembly of components developed particularly for military use is contained in Communications System AN/TSC-17. This equipment provides simultaneous twin single sideband transmission and reception in the frequency range of 1.5 to 30.0 Mc. The set is contained in two van-type vehicles and one truck mounted shelter as pictured in Fig. 5. Although greater flexibility of operation is possible, the same limitations imposed by AN/GRC-98 and AN/TSC-16 regarding air transportability apply in the case of the AN/TSC-17.

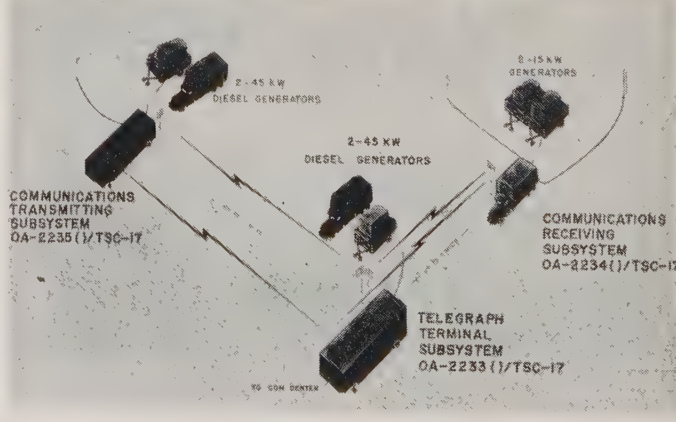

Fig. 5—Communications System AN/TSC-17.

The course that the future development effort should follow in mobile communications systems of this type is clearly indicated. The need still exists for a relatively small, compact, yet powerful strategic communications system which can provide the facilities equal to a large, fixed, global communications equipment. With the current advances being made in related fields, it is believed that the realization of a suitable design can surely be achieved.

The single vehicle communications set of the AN/GRC-26 type must also undergo further evolution to satisfy current demands for a light and compact mobile set with moderate traffic handling capability. Future development can fulfill these needs. The advantages of single sideband emission as a means of communication have been told and retold many times, so that it is to be expected that adoption of this type of transmission by all services will ring down the curtain on many of the older tactical communications sets. Development plans have existed for some time for a family of single sideband sets in the 25-, 50- and 100-mile class for U. S. Army tactical use. The fruition of these Signal Corps developments should assure mobile communications reliability not heretofore known.

Multichannel Radio Communication Within the Army*

LAWRENCE G. FOBES†

Summary—**Combat communications equipment is a highly specialized weapon in its own right. USASRDL has been an important factor in the development of combat communications and in the establishment of an industrial design capability for such equipment.**

An example is given by tracing the growth of Army multichannel communication systems from the radio-link equipment of the Tunisian campaign, through "backbone" radio relay employment exemplified by radio sets AN/TRC-1, AN/TRC-24, and AN/TRC-29, into tactical-mobile systems giving area coverage using AN/GRC-50, 53, 59 and 66 equipment.

Important milestones of concept and technique changes illustrate the continued progress towards reliable tactical radio communications.

Introduction

THE celebration this year of the centennial anniversary of the founding of the United States Army Signal Corps emphasizes that communication has long been recognized by the Army as playing an important role.

However, until very recent times, a high communication capacity generally referred to a large dispatch pouch, a fast horse, and a brave rider. Even World War I communications were characterized by motorcycle dispatch riders.

When war became imminent in 1938–1939, Congress made a considerable effort toward preparing for development and production of military weapons such as airplanes, artillery, small arms, etc. There was not, however, a general recognition of the fact that combat communications equipment could be a highly specialized weapon in its own right. This lack of appreciation of the importance of specialized military communication can be stated as a fact even though it cannot be charged to any one group, reason, or service [1].

Extensive Army maneuvers in 1939 and 1940 alerted the Army to the need of special communication for combat operations. Funds were appropriated in June, 1940. This permitted implementation of a series of five-year plans which had been drawn up by USASRDL (pronounced "Usa-sard-el"), Fort Monmouth, which was then called the Signal Corps Laboratory. The funds were very modest indeed, but the request was initially considered to be a fantastic requirement for communications.

To meet these new requirements, the laboratory expanded from a modest 250 civilian employees and a handful of officers (in June, 1940, about 50 people were available for communications). It was also necessary to enlarge facilities and inaugurate a large development program. By October, 1942, the adjustment was nearly complete upon the movement of an efficient development team into new quarters. These quarters became known as Coles Signal Laboratory, housing the communication portion of the Army Signal Laboratories development effort.

USASRDL, anticipating that rapid movement of troops would be the distinguishing feature of World War II and that the troops would soon outrun wire systems, programmed both a highly mobile long-range radio set, the famed SCR-299, and a radio-relay system.

Radio Link Introduction

The first radio-relay system (originally called radio-link equipment) was accumulated in the fall of 1941,

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

and a demonstration was given in North Carolina maneuvers by Major J. D. O'Connell,[1] W. S. Marks, J. Hessel, and others of the Laboratory, to demonstrate the principle of main-axis communication by means of repeaters.

The utility of this type of equipment was not recognized by the troops until the spring of 1942 when it was shipped to North Africa. This original equipment consisted of commercial Motorola 50-watt equipment including 250-watt amplifiers, and was only a single-channel voice-relay system. The Laboratory, in introducing this new concept of radio-link employment, not only furnished the equipment, but also supplied the operations personnel from its civilian staff. Captain O. D. Perkins with J. J. Kelleher, Russell A. Berg, Joseph H. Durrer, Victor J. Colaguori, Ferdinand W. Niedt, and Harold H. Kinnaman of Coles Signal Laboratory formed the introductory team.

This team did yeoman service in furnishing "emergency" communication during the Tunisian campaign, extending service from Algiers to Bizerte in Tunisia. These circuits carried the bulk of all operational and administrative traffic to and from the Second Corps, pending the establishment of wire lines.

From the opening of the Sicilian Campaign on July 7, 1943, until August 9, 1943, a circuit was operated from Tunis to Malta, a total distance of 243 miles over water. As additional circuits were established they were executed with the radio-relay equipment, generally between Fifteenth Army Group Headquarters and the American Fifth and British Eighth Armies. A very important need of radio relay was demonstrated in supplying traffic into the Anzio beachhead, which reached a peak word group traffic flow of 20,000 word groups a day [2].

The Army troops became aware that reliable radio communication, as the only means of communication between the beachhead and the bulk of the Army forces below the beachhead, was indeed an important offensive and defensive "weapon."

Early in the war it was realized that voice traffic requirements would exceed prior usage, and the gap between field wire and fixed-pole line construction was bridged by a spiral-four system of cable which could, by means of telephone carrier equipment, support more than one voice channel. Telephone and telegraph terminals CF-1 and CF-2 were developed and introduced to provide a four-voice channel (3+1) capacity per cable.

Recognizing that there would be shortcomings in the single channel systems using commercial equipment, USASRDL started development of an improved four-voice channel radio-relay equipment. This development started late in 1942, nearly a year before the radio-link equipment had been accepted by the field services.

[1] Later Lieutenant General J. D. O'Connell, Chief Signal Officer, 1955–1959.

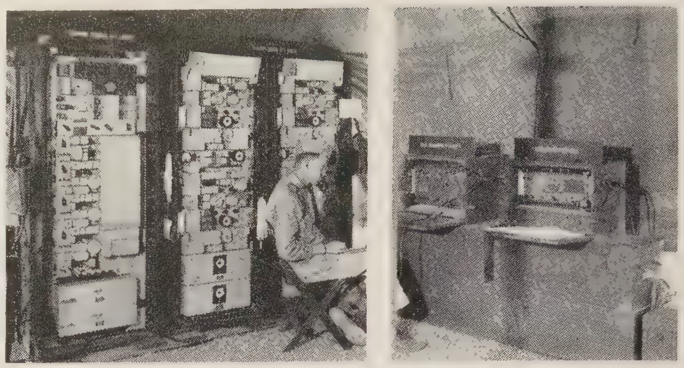

Fig. 1—AN/TRC-1, a 4-voice-channel terminal.

This radio-relay set, the famous "ANTRAC" of World War II (the AN/TRC-1), became the first specialized military radio-relay set used by the Armed Services. Fig. 1 shows the CF-1 and CF-2 carriers in action with the AN/TRC-1.

This AN/TRC-1 was first used in quantity in the invasion of Normandy and France. Once again the successful introduction of a new equipment and the new concept of multichannel radio-relay depended upon sending civilian laboratory engineers into the combat area with the equipment. Amory H. Waite and Victor J. Colaguori of USASRDL accompanied the equipment and rendered valuable service to the armies in France.

The dawn of D-Day, June 6, 1944, saw facilities installed in England and ready for the cross-channel operation to Normandy. When it was considered safe to land the valuable radio sets on June 8, 1944, it took only two hours to establish communication with England. The initial service was the transmission of vital air-reconnaissance information by facsimile. This transmission represents the first transmission of facsimile picture information to the United States forces in France; it again proved that communication is an important factor in the successful employment of weapons. This link was soon converted to voice-channel operation with the addition of the telephone carrier equipment.

There is a close parallel between the discovery that the World War I airplane, introduced as an observation platform, could also be used as a highly mobile machine gun emplacement and an efficient bomb carrier, and the growth of emergency radio-link communication in Africa into an integrated radio-relay system providing vital communication in direct support of tanks and other weapons in France. Both became vital weapons in their own right.

A typical employment of radio relay by the United States Third Army, using its full mobility capability, occurred during General Patton's dash across France. It was possible to keep up with the rapid progress from the St. Ló breakthrough by radio relay, which became the communication means until wire could subsequently be installed. The successful employment of armor as a weapon required radio communication as an essential integral ingredient.

As time progressed, the radio-relay coverage in Europe became equivalent in size to that from New York to Chicago and from Detroit to Atlanta. Its successful operation was emphasized by Major General W. Rumbough, Chief Signal Officer, European Theatre of Operations, who stated, "It is believed that this operation marks an important milestone in military radio communication. Tactical field radio equipment has successfully been integrated with wire-line and terminal equipment to form a system comparable in reliability and traffic capacity to an all-wire system."

Combat Microwave

During 1941 and 1942, while the major effort was being concentrated on link equipment, the USASRDL simultaneously pioneered in another area of equipment design, that of small portable voice channel equipment for combat troops.

Oddly enough, the goal of this program was to replace the signal light by radio and to give it a voice. Several designs were developed and tested both internally and with the aid of commercial companies (Westinghouse, General Electric, Hazeltine, Sylvania, and RCA) in 1942. These systems varied from the use of triode tubes to the limit of their frequency range, then approximately 300 Mc, to a 4000-Mc unit using the newly developed klystron tube.

The techniques which had to be used were in their infancy, and all of these units suffered from the common faults of too great a battery requirement, insufficient antenna directivity, and fragile laboratory type RF circuitry. Thus, they never saw troop application.

The program to provide small lightweight radio communication of wire-circuit quality continued with the development of the AN/PRC-3 "Hatbox" radio relay by Chester Sharp of USASRDL [5]. It was a technical achievement in simplicity, considering the techniques of the day (1945). This equipment had just entered production at the end of the war, and its production was terminated along with other war material cut-backs at that time.

High Traffic Radio Relay

USASRDL, recognizing the value of, and anticipating the widespread acceptance of, radio link and radio relay as a weapon, late in 1942 sent a team, including representatives of RCA, Bell Telephone Laboratories, and Major L. Seibert, Sidney Metzger, and Rudolph Riehs of the Signal Corps, to England to view their experimental wireless set X-10, a unique 4000-Mc, eight-voice channel set using the new radar-like PPM (pulse position modulation). As a result of this visit, the Laboratory initiated a research and development project for a 6-cm klystron-powered radio and a 25-cm magnetron-powered set. These two equipments represented the first successful communication use of microwave frequencies within the United States.

Bell Telephone Laboratories was selected to engineer the 4500-Mc set, and RCA the 1500-Mc set. The choice of 8-voice channels for these equipments was made on the premise that they would net with the British X-10 and would handle the traffic from two radio-relay carriers CF-1 of four channels each. These radio-relay sets became the AN/TRC-6 and AN/TRC-5 [4].

While not high traffic sets by today's standards, it must be remembered that not even single-channel radio relay had been accepted by the military users, and that the program represented a considerable foresight on the part of the Laboratory.

In January, 1943, work was begun on the AN/TRC-6, and during September and October the preliminary models were operated over several test circuits. These sets were turned over to the Signal Corps in November, 1943, and received extensive testing in the vicinity of Cape May, N. J., under the direction of E. Baum and C. DeBlasio. A number of modifications were found desirable in the original equipment, and work was started on refined models. Meanwhile, additional testing was performed between Beers Hill, Middletown, N. J., and Harriman, N. Y., during December of that year.

Delivery of four of the improved models was accomplished by August, 1944. This permitted the first operation with a relay point in the system. Tests were conducted between stations located at Beers Hill, Neshanic, N. J., and Perrineville, N. J., permitting two-hop circuits of about 40 miles.

During September, 1944, the first "long-haul" microwave radio-relay circuits were installed on a multihop system extending from Beers Hill, near Fort Monmouth, N. J., to Gratz, Pa., a distance of 140 miles. This was the first large scale troop test of microwave systems, and it was directed by civilians of USASRDL, assisted by engineers from BTL and Western Electric who fabricated the models. These tests proved the feasibility of troop use of microwave radio relay for teletype, facsimile, and voice traffic by both audio patch repeatering and by direct video repeatering.

These field tests were not comprehensive enough to assure satisfactory employment by ground troops, since all-weather tests were not included. Army acceptance of this type of equipment for rear area usage seemed assured. Work was started on a further improved model which entered a limited 50-unit production under laboratory sponsorship as the AN/TRC-6 (XC-2).

Military personnel trained on the Pennsylvania circuit arrived in France on November 5, 1944, to supervise the introduction of the AN/TRC-6 to the European Theatre. Because of the tactical situations existing and some damage resulting from shipment, the equipment was not operational until January 21, 1945, when several demonstration circuits were installed from Verdun, 23 miles to Buzancy, thence 25 miles to Suippes.

In March, 1945, these equipments linked Eschweiler with Duren in Germany, providing the only means of

communication from the Twelfth Army Group to the First Army during a two day period when cable communications were cut. Later the Verdun-Buzancy link was moved to furnish an extension of the Eschweiler-Duren link. A relay was established at Duren and a forward terminal near Euskirchen at First Army Headquarters.

When more equipment arrived in April, 1945, advanced circuits were installed between several Army groups under direction of USASRDL technical officers. As the Third Army advanced into Germany, constant communication between it and the Twelfth Army Group was maintained over nearly 300 miles, using two terminals and three repeater stations. The link extended from the Twelfth Army group near Frankfort to the Third Army in southern Germany.

Meanwhile, the shift of activity in the Pacific areas to the more northern islands placed the emphasis on mountainous terrain. A two-phase test plan was put into effect to obtain advance operational data for such employment. Phase I was to be mountain top operations in California simulating the terrain of the northern Pacific islands, and Phase II, chosen for its freedom from high level ducts and the existence of trade wind type low level conditions, was to be low water shots across the Gulf of Mexico in Florida.

In California two different radio relay circuits were installed; the first, under the direction of the late Fred Morf of USASRDL, from June, 1945, to October, 1945, connected San Francisco to San Diego over a six jump path characterized by several relay points installed in the mountains from 4200 feet to 8000 feet elevation [3]. A notable first was the operation of both 1500-Mc and 4500-Mc equipment over a single jump of 170 miles. As the summer months arrived this long path became somewhat unreliable and a mobile repeater installation shown in Fig. 2 was dispatched to the 200-foot elevation midpoint of the path. The second path, under the technical direction of the author, of USASRDL, connected San Francisco to Los Angeles (San Pedro) from October, 1945, to February, 1946. This link operated through relay stations located below 3400 feet elevation along the coast range in order to avoid anticipated snow conditions at the higher sites and included a 114-mile single-hop overwater path. The first system had a length of 527 miles plus a 25-mile spur link, and the second path had a length of 388 miles, these being the longest microwave radio relay circuits installed up to that time.

In addition to being the training ground for troops in anticipation of combat theatre employment, the site was selected to gain additional technical information. Much study was done on the problem of multipath reception, with detailed studies of angle-of-arrival, shielded site, and complementary space diversity conducted under the direction of Thomas J. Carroll, Office of Chief Signal Officer.

Upon cessation of hostilities with Japan, it was decided to continue the comparative tests, as they afforded an excellent opportunity for further engineering study and evaluation. The tests were discontinued in February, 1946, due to the impending discharge of most of the enlisted men available for the operation.

Fig. 2—Mobile installation at "Rambler," south of Madera; comparative tests of radio relay equipment.

By November, 1945, a number of microwave radio links had been installed in Japan for use by the Fifth Air Force, and greater use was anticipated. In line with the USASRDL policy of advancement of technical and development capabilities of industry, the AN/TRC-5 and AN/TRC-6 were rapidly declassified from "Secret" to permit dissemination of the information throughout industry. Many consider these sets to be the fountainhead of the huge commercial radio-relay industry which exists today.

The California tests were the last large-scale field troop exercise conducted with laboratory-procured equipment under the direction of laboratory military and civilian personnel. The importance of communication as a weapon had become generally accepted, and, henceforth, large-scale field operations of communications became routine within troop organizations.

USASRDL emphasis was again concentrated upon the development and advancement of basic communications, and the refinement of design stressing ease of operation (human engineering) and greater operational reliability, through improved design and improved maintenance techniques.

The future of radio relay seemed assured. Under USASRDL sponsorship Raytheon engineered the AN/TRC-16, pioneering in the 8000-Mc range, while General Electric engineered radio set AN/TRC-26, which combined the best electrical features of the latest AN/TRC-5 (XC-4) and AN/TRC-6 (XC-4) models in an improved mechanical package stressing ease of operation.

The 4- and 8-voice-channel capacity of these sets soon proved to be inadequate, and designs were introduced for 12- to 46-voice-channel systems and television bandwidth systems, capable of operation over as many as 20 tandem links, of which the AN/TRC-24, AN/TRC-25, AN/FRC-23, and AN/TRC-29 are typical.

Operational Concepts

Radio-link service introduced by USASRDL in 1940, expanded by 1942 into the multichannel radio-relay operational concept of World War II. The operational employment of these equipments was for long-distance in-line point-to-point "backbone" communications on an interim or emergency basis until wire circuits could be installed. For such systems, 200- to 500-mile distances became common.

Laboratory radio engineers have long been confident that radio communication could, in its own right, give a traffic capability and reliability as a prime method of communication without relying upon wire. Radio sets AN/TRC-5 and AN/TRC-6 were designed on this basis. The backbone concept reached its zenith in 1955 with the 45-voice-channel Radio Set AN/TRC-29, Fig. 3, a twenty-tandem-hop radio-relay design including provisions for two- and eight-channel spur circuits and VHF radio keying circuits to mobile vehicles for pipeline and other specialized services.

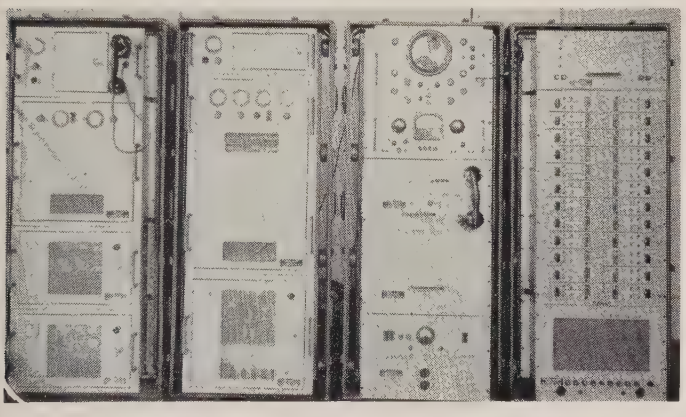

Fig. 3—Radio set AN/TRC-29 with multiplexer set AN/TCC-13.

However, lessons learned during the Korean conflict foretold the end of point-to-point backbone systems, and a transition had to be made from "line" to "grid" thinking for area coverage. Modern fire-power capabilities further made the change mandatory, since it is now easy to destroy a radio-link relay point. Alternate routing capability for bypassing these outages is required.

The area coverage concept is similar to the intercity network of toll-quality, common-user, telephone trunks which link the cities of our country. The difference is that instead of being built up over the years on wire systems, growth is measured in hours and mobile, tactical, radio-relay sets are employed in place of cables.

The most radical idea of this concept from the troop viewpoint is not the area coverage but, rather, the idea of a "common user" facility. While this philosophy of a common ownership service provided by a telephone company has seldom been questioned on a commercial basis; the operating efficiencies have not yet been adapted to combat groups, which have for generations relied entirely on a communication capability within their immediate command.

The equipment designed for the long haul repeatered relay system could not meet efficiently the dispersal and mobility needs of the area system. A major change in equipment planning was required.

A program was initiated in 1955 with RCA, Westinghouse, Philco, ITTL, Raytheon, and National to provide a new family of tactical radio relay sets to meet the needs of the area system. Radio sets AN/GRC-50, AN/GRC-53, AN/GRC-59, AN/GRC-66, AN/GRC-62, and AN/MRC-80 resulted.

These equipments represent great improvements in technical performance, ease of operation, reliability, maintainability, ruggedness, use of transistorization, and modularization over the present standard issue sets.

Packaging

The one area where the specialization required of combat communications stands out beyond all other considerations is equipment packaging. Packaging is referred to in the broadest sense, including the equipment environment. The requirements for combat equipment make it necessary to have extremely reliable operation after having undergone extremes of temperature and humidity, rough handling, and transport conditions which would immediately void the guarantee of any commercial electronic product. It has been in this area that USASRDL has contributed its resources towards improved parts, methods, and industrial training to bridge the gap between commercial, practical, and tactical requirements. Without the mechanical and component design research program of USASRDL, tactical equipment of modern design might well be nonexistent, since the need for parts and designs of the required type is not generated in support of quality commercial items.

The packaging requirements of tactical equipments have undergone radical changes since 1942. World War II employment concepts were based on "forward area," "intermediate area," and "rear area" operation. The radio-link and early radio-relay employment was within tents or other shelters of expediency in the forward and intermediate areas, while the rear area equipments were in buildings mounted in the commercial equipment manner.

The advent of communication requirements for areas of occupation dictated that all Army multichannel radio-relay equipment be designed to one standard, that of a tactical-mobile design suitable for division area usage. The 23-channel radio relay terminal AN/GRC-66 of Fig. 4 should be compared with radio set AN/TRC-29 of Fig. 3, which it replaces. The current equipment retains a waterproofing and cargo transit capability in which four cases of a graduated size are used, but its normal life will be in a practical "turtle" environment in shelters. Fig. 5 shows an application utilizing the waterproofing capability.

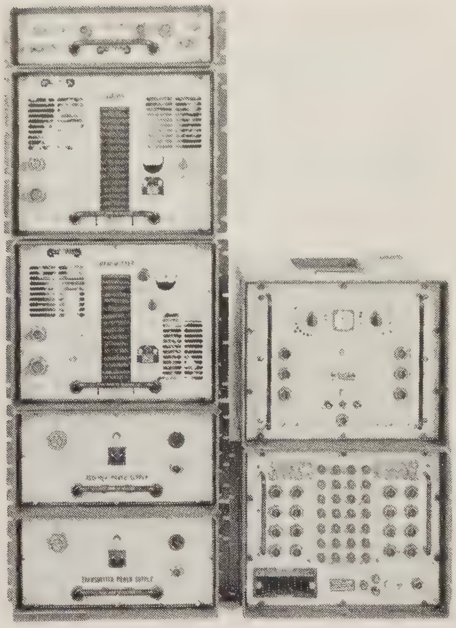

Fig. 4—Radio relay terminal. Radio set AN/GRC-66, multiplexer set AN/TCC-26 and ringer-converter CV-905, 23-voice channels.

Fig. 5—AN/GRC-53 on a mechanical mule.

Role of USASRDL

During the 1940's, the role of the Signal Corps Engineering Laboratories was quite clear-cut. It had the responsibility of introducing new equipment and new operational concepts to the Army in order to fill a communication void. In order to meet the introduction deadlines necessitated by the combat situations of an active Army, it met its responsibility by procuring equipment on an experimental (XC-1) basis and sending civilian engineers into the field for its introduction. The emphasis was clearly on expedited hardware delivery. While the types of equipment required were limited, it was possible to operate on a "cradle to the grave" basis where each engineer followed all phases of the equipment from concepts to obsolescence. Radio sets AN/TRC-1, AN/TRC-5, AN/TRC-6 and AN/TRC-8 were rushed to completion to fill the communication void on this basis.

After the war there was a feeling of optimism about the future. The emphasis of the laboratory work was redirected from hardware to research. For the first time radio-relay communication was put on a research basis, with development of concept models representing the state of the art. During this time VHF work was directed towards the elimination of quartz crystals from frequency control systems (a big bottleneck of the war) and provision of operational simplicity. The microwave program centered on techniques using traveling wave tubes and the construction of radio set AN/TRC-25, a 4000-Mc set, having a 10-Mc-wide communication channel capable of simultaneous transmission of television pictures, 100 PCM channels, 120 channels of FDM carrier, or other signals of equal bandwidth. All parameters were selected on the basis of pressing the state of the art, rather than on practical designs to immediate user requirements. The AN/TRC-25, a state of the art equipment developed by ITTL (then Federal Telecommunication Laboratories), was successfully demonstrated in January, 1959, by "remoting" radar displays, transmitting 48 PCM channels plus a video phone circuit, transmitting two simultaneous television signals, etc.

When the Korean conflict came, emphasis again quickly returned to the task of delivering practical hardware in the least possible time. Both the VHF and microwave programs were reoriented and they resulted in radio sets AN/TRC-24 and AN/TRC-29, a 12- and a 45-voice channel equipment.

The communications requirements have become more complex and the role of the Laboratory has been redefined to stress the research and development phases, as follows.

"USASRDL is a government laboratory whose *modus operandi* is to use its allocated resources to focus the maximum and best technical efforts anywhere available on the problems involved in providing the best possible

communication equipment for the Army." The Signal Corps Laboratories, until well into World War II, found it necessary to advance Army communication equipment from the cradle to the grave; from its concept to design and fabrication, performance testing, service testing, instruction of troops in its use, actual combat use of the equipment, and finally its quality control and production inspection. It was, however, early recognized that its mission could not be met by duplicating and competing with industry, but rather by establishing a broad base of industrial development capability and leading industry toward improved systems.

To this end, the Laboratory divorced its procurement, pilot-run production guidance and maintenance support functions, which are now capably handled by the United States Army Signal Material Support Agency, Fort Monmouth, N. J.

In order to concentrate further on equipment advancement, the important, but manpower consuming, function of operational evaluation was placed in the hands of the United States Army Electronic Proving Ground, Fort Huachuca, Ariz.

Thus, USASRDL with other Government and non-Government agencies, universities, and other nonprofit organizations, plus competitive, profit-making, industrial organizations, all play a major and essential part in developing communications into an efficient combat weapon [8].

Multiplexing Equipment

The story of microwave radio relay would not be complete without a review of the history of the associated multiplex and carrier equipment. The adoption of the telephone carrier CF-1 to radio represents one of the earliest applications of multichannel FM radio communications.

During World War II, the British introduction of time division multiplexing and the Army introduction of pulse position modulation (PPM) equipment opened a whole new era of small, compact, multiplexers for high traffic capacities from which stemmed a host of commercial equipments.

Post-war developments have made great strides in miniaturization of multiplexing equipment, thanks to the great progress in semiconductor research. The AN/TCC-26 providing 23 voice channels in a $17\times15\times13\frac{3}{4}$ inch volume, and the AN/TCC-27, providing 14 voice channels, both developed by RCA to USASRDL requirements, are typical examples of advanced PPM equipment.

Radio sets AN/TRC-5, AN/TRC-6, AN/TRC-29, AN/GRC-50, AN/GRC-59, and AN/GRC-66 all transmitted PPM.

The introduction of PPM by the Army in 1943 was closely followed just before the war ended (1947) by the first PCM equipments for use with Radio Set AN/TRC-6. Built by BTL, these represented the first physical embodiments of what is now classical information theory. They even included auto-correlation detection for synchronization purposes.

By 1950, Army 48-voice-channel PCM systems were a reality, although it was not until the advent of semiconductor technology that PCM design became of age, permitting small size, low power drain, tactical PCM equipments. Current Army PCM designs multiplex 48-voice channels in less space than is occupied by half an office filing cabinet. USASRDL exploitation of the advantages which can be gained through PCM time-division techniques has just begun, as is evidenced by the recent formation of a new division specializing in PCM modulation applications. BTL, ITTL, and Raytheon have made major contributions to the Army PCM development program.

The advancement of the traditional frequency division multiplexing (telephone carrier) systems has not been neglected. Each generation of design from 3+1-voice channel CF-1, through the 12+1-voice channel AN/TCC-7, to the miniaturized, transistorized, AN/TCC-24 with its 24+1-channel capability, represents a marked advancement in the art as fostered by USASRDL requirements and development guidance.

Technique Development

Just as the early aircraft lacked the desired speed and load capability to be a fully effective weapon, the early microwave radio relay sets were large and required bulky tower assemblies and used tower-top radio equipment, requiring the operator to make daily trips up the tower.

In order to make a more effective weapon, substitute antenna feed and mast systems were required which would introduce little loss and would permit ground operation.

The techniques of the day did not permit coupling the klystron transmitter tubes to the antenna through the required 50-foot lengths of waveguide. In the spring of 1945, USASRDL calculations showed that a 45-degree reflector antenna of reasonable size would result in an operational system. During July and August, 1945, a system was installed and tested under the direction of C. G. DeBlasio which used two 45-degree reflectors on a 50-foot tower for the transmitted and received signal.

On the basis of these tests, work was initiated at BTL to incorporate operational improvements in the AN/TRC-6. They derived a greatly improved final version of the AN/TRC-6, the XC-4 model, which incorporated a single reflector on a 50-foot mast and introduced the use of a diplexer to couple the transmitter and receiver into a single ground mounted antenna.

This equipment was caught in the end of the war cut-back of production, and it remained for commercial system requirements to introduce the widespread use of reflector antenna systems.

Fig. 6—Flat plate reflector. Part of radio set AN/TRC-6 (passive repeater test) raised in operating position at Beers Hill, N. J. repeater station.

During August, 1946, passive repeater tests were conducted under the direction of John Egli of Coles Signal Laboratory to verify theoretical considerations for the use of passive repeaters of many types. These included waveguide coupled dishes, double reflectors, as shown in Fig. 6, and the conventional single-reflector systems to receive, transfer, and retransmit to the station beyond. Distances between the "passive repeater" reflector and the hidden terminal station were varied from 5 to 1.6 miles.

Reflector antennas were, in turn, soon displaced in Army equipment in 2000- and 4500-Mc applications by a revolutionary new transmission line developed by Dr. George Goubau of the USASRDL. The surface wave transmission line [6], or *G* line as it is often called, guides the RF energy along a dielectric coated wire at 1/7 the db loss of acceptable tactical coaxial cables and without requiring large antenna structures of the reflector antenna type. Fig. 7 shows a typical *G* line application.

A further refinement of duplexing both a transmitter and a receiver into a single antenna was introduced soon after 1945, and became the normal mode of operation for military microwave.

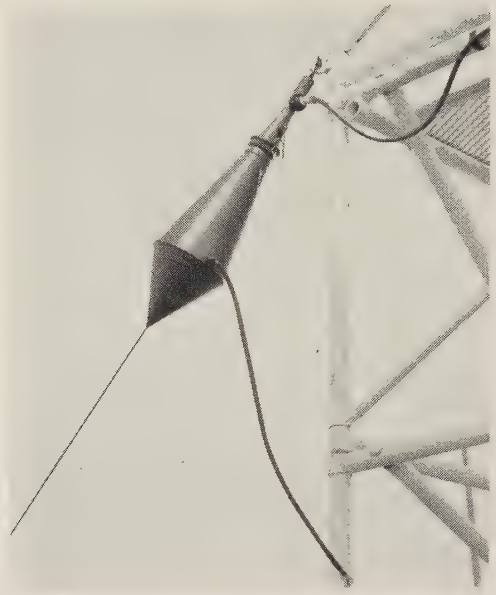

Fig. 7—Upper launcher connected to tower AB/216/U.

The design of Army digital frequency modulation radio-relay systems on a minimum bandwidth basis, using Gaussian filtering [10], [11], has been a major technical advancement in the communication art. Additionally, the design of current Army relay equipment on a building-block basis permits a design and use flexibility not previously attainable. A typical design using these design principles is shown in Fig. 8, opposite.

Recent USASRDL pioneering in the communications field includes an experimental millimeter wave system, operating at about 35 kMc for short-range voice use. This was developed by USASRDL with Emerson Research Laboratories, under the direction of C. Sharp of the Signal Corps. This two-way system uses nonsynchronous coherent pulse modulation and has a capability of 21 voice channels.

Current equipment designs, including fully transistorized FDM, PPM, and PCM multiplexers assembled in modular form and microwave equipment transistorized except for four tube functions, make practical use of advanced techniques not yet included in commercial equipment for the same type of service. These designs are less than 1/10 the size of similar equipment of a decade ago and are capable of two to four times the voice traffic at greatly enhanced reliability.

Further evidence of USASRDL leadership in the communication field was the recent communication first, the transmission of a 12-voice-channel pulse code modulation signal 93 miles from Tobyhanna Signal Depot, Pennsylvania, to the Hexagon, Fort Monmouth, N. J. This represents the first known transmission of high-bit rate PCM information over greater than line of sight distances. This tropospheric scatter transmission at a rate exceeding 500 kilobits was directed by Irving Kullback of the Laboratory, and is expected to be the forerunner of many important long distance communication appplications.

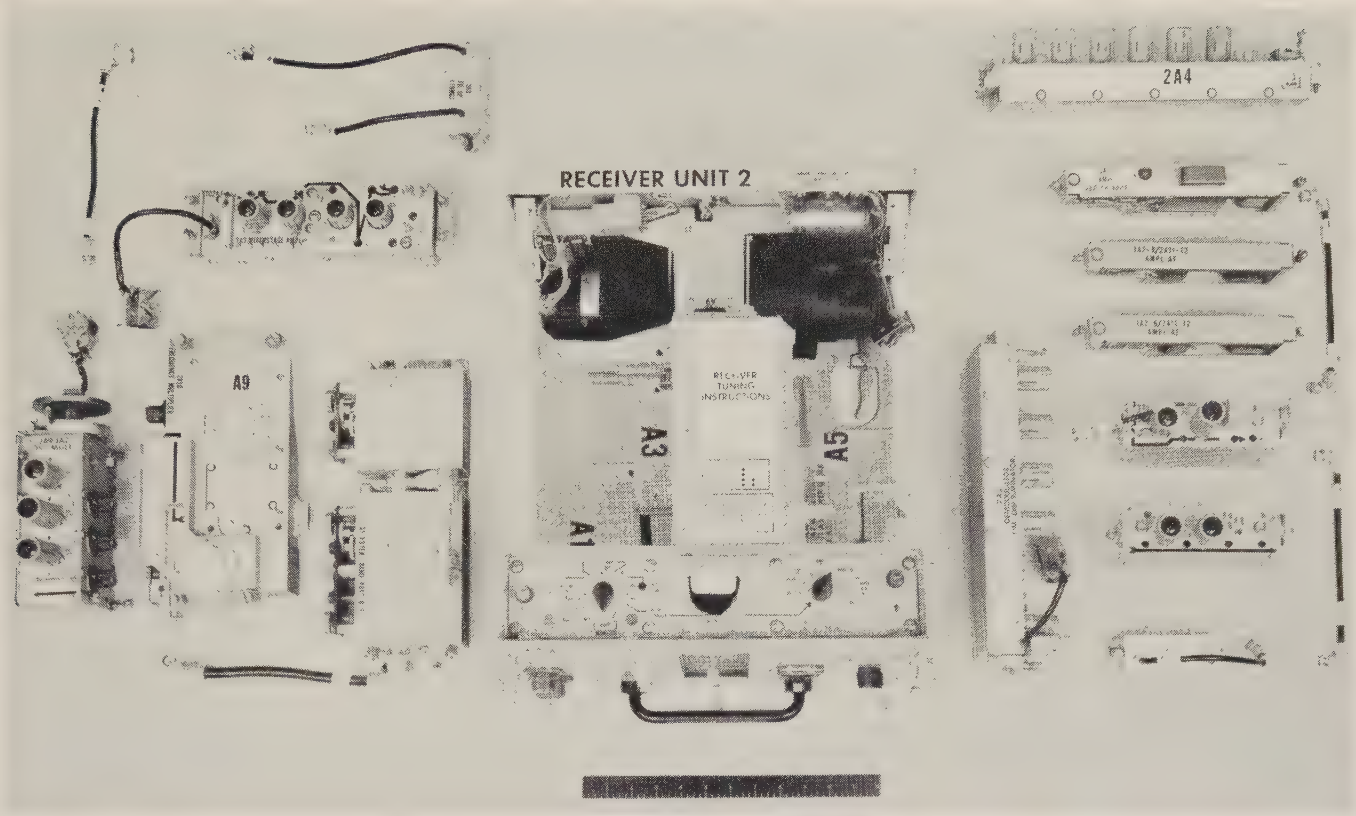

Fig. 8—Microwave receiver of building block design.

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Automatic Data Processing Equipment Program for the Field Army*

MILTON A. LIPTON†

Summary—In 1956, the U. S. Army Signal Corps was directed to undertake the development of automatic data processing (ADP) systems for the Army in the field. The development of a mobile, general purpose, digital computer, named MOBIDIC, was initiated concurrently with an Army-wide analysis of the specific tactical application-in which it could suitably be used. As the application studies progressed, it became evident that a family of computers was required for the different tactical echelons. The FIELDATA Equipment Program evolved and is now current for this purpose.

This program encompasses major activities in computer design, programming techniques, data transmission equipment, input-output equipment, advanced techniques, and human factors studies, the last named being considered most critical for successful tactical usage of ADP. A set of standards has been formulated and adopted for all FIELDATA equipment in the factors of alphanumeric code, control function code, computer word structure, computer order code and equipment interconnection methods.

The first MOBIDIC has been delivered to the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J., and is now undergoing acceptance and evaluation testing.

A crash program was recently assigned to the Signal Corps for the construction and delivery in this calendar year of a MOBIDIC especially arranged for a large-scale logistics function of the Seventh U. S. Army in Europe. The total Signal Corps role in this program includes equipment design and fabrication, system analysis and programming, troop training, and initial system operation.

The success of ADP in the Field Army will now rest with the yet-to-be-determined validity of system concepts, merits of the equipment designs and degree of user acceptance.

Inception

COMMERCE and industry have evinced an explosive interest in Automatic Data Processing as a means of reducing administrative and overhead burden, accelerating the interchange of records and operational data, and providing timely analysis of operations to management levels. The successful uses of ADP for such purposes are manifest. For corresponding reasons, the Army in the field has turned to ADP. The amazing diversification of materiel handled (tens of thousands of replacement and maintenance parts types alone), the decentralization of Field Army organization dictated by threat of nuclear attack, and the need for increased tempo and quick response in the face of such threat—all are aspects of Field Army operations that force consideration of the potential use of ADP.

Accordingly, the U. S. Army Signal Corps was directed in 1956 to undertake the study and development of tactical Automatic Data Processing Systems for the Field Army which could be employed to advantage in the areas of administration (including personnel) intelligence, logistics, and combat operations. The development of a *MOBI*le, *DI*gital, fully militarized and transistorized general purpose *C*omputer named *MOBIDIC* was initiated.

The scheduled delivery date promulgated in 1956 by the Signal Corps and its contractor, Sylvania Electric Products Company, was December, 1959. Parenthetically, it is stated with commendation to this contractor that the first MOBIDIC was delivered in December, 1959.

Concurrent with this computer development, an Army-wide exploration of specific tactical applications suitable and valid for ADP was initiated in the various Technical Service Schools and Boards. As these analyses progressed it became evident that the variety of applications with potential validity demanded a family of computers offering a range of data processing capabilities for use at the different tactical echelons of command.

Signal Corps activities proceeded in a number of different areas, such as tactical equipment development, system concepts, application analysis, application programming and corresponding fixed-plant efforts for all of the above. It is the purpose of this paper to describe only the tactical equipment development program.

FIELDATA Equipment Program

The FIELDATA Equipment Program was undertaken and is currently being pursued to provide a family of compatible, stored program, general purpose digital computers and associated equipment which, in a minimum number of types, will satisfy the ADP needs of the Field Army. This program is not a simple one of equipment design, however. The complex and dynamic nature of the technology, the interdependence of computer logic and programming, the communications aspects of data processing, and the criticalness of skilled tactical personnel have required major activities in six distinct areas in order to provide a balanced program of equipment development. These areas are computer design, programming techniques, data transmission equipment, input-output equipment, advanced techniques, and human factors studies. They are described in detail below.

Central to the entire development program has been the theme of family uniformity and compatibility. This theme has been emphasized because of the tremendous tactical advantages that accrue therefrom in logistics, personnel training, and maintenance techniques. For this reason it is the intent (and directive) of the U. S. Army to employ only this family of computers in tactical applications, except where special purpose computers prove to be particularly applicable and advantageous.

A set of standards has been formulated and adopted

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

for all FIELDATA equipment covering such items as alphanumeric code, control function code, computer word structure, computer order code, signal characteristics and equipment interconnection methods. The alphanumeric and control function codes combine in the FIELDATA language code, a very useful eight-level data language that has been adopted by the U. S. Army, U. S. Navy and U. S. Air Force as a unified design objective and is also being considered by the Electronics Industries Association as an industrial standard. Table I shows the FIELDATA Standard Code Table. While many people have contributed to the FIELDATA Equipment Program's direction and execution, one person in particular must be named. Captain W. F. Luebbert, U. S. Army Signal Corps, provided a degree of genius, energy, and inspiration that warrants special mention at this time.

Computer Design

The family of FIELDATA computers includes MOBIDIC, INFORMER, BASICPAC, and COMPAC. These range from a large scale processor in a trailer van installation to a small scale processor which is man portable. All of these computer designs are fully militarized and are capable of withstanding wide extremes of temperature in storage (−80°F to +180°F), wide extremes of temperature in operation (−25°F to +140°F), wide ranges of humidity, shock, vibration, power supply fluctuations, etc. All are stored program, general purpose digital processors. All are synchronous in operation, using a one-megacycle clock rate, a 38-bit world length, a single-address form of instruction with some two-address capabilities, and magnetic core internal memories. Their circuitry is solid state, using miniature components, with several variations in high density component packaging. Their circuits are arranged in basic units of element cards. Several element cards plug into a logic board. Several logic boards plug into a package module. Several package modules are grouped to form a central processor with any desired arrangement of memories, buffers, converters, etc. Single-bit, odd-parity check is employed throughout.

This modular form of construction, when combined with computer-operated error check and diagnostic programs, provides a maximum of maintainability, permitting localization of fault or malfunction down to a module, logic board, or element card. Replacement, with restoration of operation, can be rapid. Repair, if

TABLE I

FIELDATA Standard Code Table

The complete FIELDATA Code including the alphanumeric characters and the control functions is presented below in the standard 8-bit form. It uses odd parity and the basic pattern for control (1 = data, 0 = control).

FIELDATA Standard Code Table

7	6	5	4	3	2	1	0
P	C	I_2	I_1	D_3	D_2	D_1	D_0

Alphanumeric				Control			
Character	7 6 5 4 3 2 1 0 P C I I D D D D	Character	7 6 5 4 3 2 1 0 P C I I D D D D	Character	7 6 5 4 3 2 1 0 P C I I D D D D	Character	7 6 5 4 3 2 1 0 P C I I D D D D
Master Sp.	0 1 0 0 0 0 0 0	)	1 1 1 0 0 0 0 0	Dial 0	0 0 1 0 0 0 0 0	Blank/Idle	1 0 0 0 0 0 0 0
Upper Case	1 1 0 0 0 0 0 1	—	0 1 1 0 0 0 0 1	Dial 1	1 0 1 0 0 0 0 1	TST	0 0 0 0 0 0 0 1
Lower Case	1 1 0 0 0 0 1 0	+	0 1 1 0 0 0 1 0	Dial 2	1 0 1 0 0 0 1 0	TCL	0 0 0 0 0 0 1 0
Line Feed	0 1 0 0 0 0 1 1	<	1 1 1 0 0 0 1 1	Dial 3	0 0 1 0 0 0 1 1	Tab	1 0 0 0 0 0 1 1
Carriage Return	1 1 0 0 0 1 0 0	=	0 1 1 0 0 1 0 0	Dial 4	1 0 1 0 0 1 0 0	Control CR	0 0 0 0 0 1 0 0
Space	0 1 0 0 0 1 0 1	>	1 1 1 0 0 1 0 1	Dial 5	0 0 1 0 0 1 0 1	Control Spa.	1 0 0 0 0 1 0 1
A	0 1 0 0 0 1 1 0	-	1 1 1 0 0 1 1 0	Dial 6	0 0 1 0 0 1 1 0	Control A	1 0 0 0 0 1 1 0
B	1 1 0 0 0 1 1 1	$	0 1 1 0 0 1 1 1	Dial 7	1 0 1 0 0 1 1 1	Control B	0 0 0 0 0 1 1 1
C	1 1 0 0 1 0 0 0	*	0 1 1 0 1 0 0 0	Dial 8	1 0 1 0 1 0 0 0	Control C	0 0 0 0 1 0 0 0
D	0 1 0 0 1 0 0 1	(	1 1 1 0 1 0 0 1	Dial 9	0 0 1 0 1 0 0 1	Control D	1 0 0 0 1 0 0 1
E	0 1 0 0 1 0 1 0	"	1 1 1 0 1 0 1 0	SOC	0 0 1 0 1 0 1 0	Control E	1 0 0 0 1 0 1 0
F	1 1 0 0 1 0 1 1	:	0 1 1 0 1 0 1 1	SOB	1 0 1 0 1 0 1 1	Control F	0 0 0 0 1 0 1 1
G	0 1 0 0 1 1 0 0	?	1 1 1 0 1 1 0 0	SOD	0 0 1 0 1 1 0 0	Control G	1 0 0 0 1 1 0 0
H	1 1 0 0 1 1 0 1	!	0 1 1 0 1 1 0 1	SPARE	1 0 1 0 1 1 0 1	Control H	0 0 0 0 1 1 0 1
I	1 1 0 0 1 1 1 0	,	0 1 1 0 1 1 1 0	SPARE	1 0 1 0 1 1 1 0	Control I	0 0 0 0 1 1 1 0
J	0 1 0 0 1 1 1 1	⊕	1 1 1 0 1 1 1 1	STOP	0 0 1 0 1 1 1 1	Control J	1 0 0 0 1 1 1 1
K	1 1 0 1 0 0 0 0	0	0 1 1 1 0 0 0 0	RTT	1 0 1 1 0 0 0 0	Control K	0 0 0 1 0 0 0 0
L	0 1 0 1 0 0 0 1	1	1 1 1 1 0 0 0 1	RTR	0 0 1 1 0 0 0 1	Control L	1 0 0 1 0 0 0 1
M	0 1 0 1 0 0 1 0	2	1 1 1 1 0 0 1 0	NRR	0 0 1 1 0 0 1 0	Control M	1 0 0 1 0 0 1 0
N	1 1 0 1 0 0 1 1	3	0 1 1 1 0 0 1 1	EOBK	1 0 1 1 0 0 1 1	Control N	0 0 0 1 0 0 1 1
O	0 1 0 1 0 1 0 0	4	1 1 1 1 0 1 0 0	EOB	0 0 1 1 0 1 0 0	Control O	1 0 0 1 0 1 0 0
P	1 1 0 1 0 1 0 1	5	0 1 1 1 0 1 0 1	EOF	1 0 1 1 0 1 0 1	Control P	0 0 0 1 0 1 0 1
Q	1 1 0 1 0 1 1 0	6	0 1 1 1 0 1 1 0	EOC	1 0 1 1 0 1 1 0	Control Q	0 0 0 1 0 1 1 0
R	0 1 0 1 0 1 1 1	7	1 1 1 1 0 1 1 1	AKR	0 0 1 1 0 1 1 1	Control R	1 0 0 1 0 1 1 1
S	0 1 0 1 1 0 0 0	8	1 1 1 1 1 0 0 0	RPB	0 0 1 1 1 0 0 0	Control S	1 0 0 1 1 0 0 0
T	1 1 0 1 1 0 0 1	9	0 1 1 1 1 0 0 1	ISN	1 0 1 1 1 0 0 1	Control T	0 0 0 1 1 0 0 1
U	1 1 0 1 1 0 1 0	'	0 1 1 1 1 0 1 0	NISN	1 0 1 1 1 0 1 0	Control U	0 0 0 1 1 0 1 0
V	0 1 0 1 1 0 1 1	;	1 1 1 1 1 0 1 1	CWF	0 0 1 1 1 0 1 1	Control V	1 0 0 1 1 0 1 1
W	1 1 0 1 1 1 0 0	/	0 1 1 1 1 1 0 0	SPARE	1 0 1 1 1 1 0 0	Control W	0 0 0 1 1 1 0 0
X	0 1 0 1 1 1 0 1	.	1 1 1 1 1 1 0 1	SAC	0 0 1 1 1 1 0 1	Control X	1 0 0 1 1 1 0 1
Y	0 1 0 1 1 1 1 0	Special	1 1 1 1 1 1 1 0	SPC	0 0 1 1 1 1 1 0	Control Y	1 0 0 1 1 1 1 0
Z	1 1 0 1 1 1 1 1	Idle	0 1 1 1 1 1 1 1	DELETE	1 0 1 1 1 1 1 1	Control Z	0 0 0 1 1 1 1 1

economically warranted, can be accomplished at a convenient time and place.

Identical element cards, logic boards and package modules are not used throughout the FIELDATA family. The rapid advances in this technology argue against rigid standardization and have made newer approaches attractive in successive developments.

MOBIDIC is the largest of the processors in both size and capacity. It is trailer van mounted and field mobile and is intended for general computational and data processing applications at Army or Theatre level. It is all parallel in internal operation, has a memory access time of eight microseconds, and can accomplish 40,000 typical operations per second. Its order code includes all of the 52 FIELDATA instructions. Five forms of MOBIDIC are under development. These employ, principally, variations in input-output equipment to accommodate the particular needs of the tactical application for which intended. One application in particular is described later in this paper. Fig. 1 indicates a typical MOBIDIC computer arrangement.

INFORMER is a medium capacity processor with a particular capability for information search and retrieval. It contains a unique logical search facility and random access external memory. It is shelter-mounted, is field transportable by a $2\frac{1}{2}$ ton truck, and is intended for intelligence and file-searching applications at Division level and higher. It employs a technological innovation of magnetic logic circuitry. It is parallel by bit, serial by character; it has a memory access time of 8 μsec, and can accomplish 30,000 typical operations per second. Its order code includes all of the fifty-two FIELDATA instructions.

BASICPAC is a medium capacity computer for general computational and data processing applications at Division level and higher. It is shelter mounted and field transportable by a $2\frac{1}{2}$ ton truck. It is parallel by bit, serial by character, has a memory access time of 12 μsec, and can accomplish 25,000 typical operations per second. Its order code includes forty of the fifty-two FIELDATA instructions. Fig. 2 shows a typical BASICPAC arrangement.

COMPAC is the smallest computer in the FIELDATA family. It is man transportable, with a size of 9 cubic feet and a weight of 160 pounds. It is intended for general computational and data processing applications forward of Division. It is arranged for rapid changeover from general purpose to special purpose console where the application warrants. It is parallel by bit, serial by character, has a memory access time of 12 μsec, and can accomplish 25,000 typical operations per second. Its order code includes twenty-eight of the fifty-two FIELDATA instructions. Fig. 3 shows a front view of the COMPAC.

All of these computers permit great flexibility in the number and arrangement of memories, input-output converters, and input-output devices, and thus can accept a gamut of applications. All can be arranged for

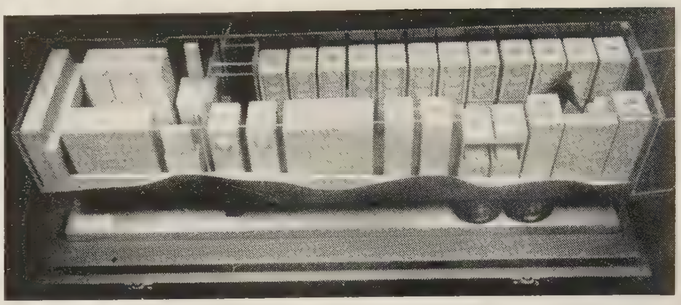

Fig. 1—Typical MOBIDIC computer arrangement.

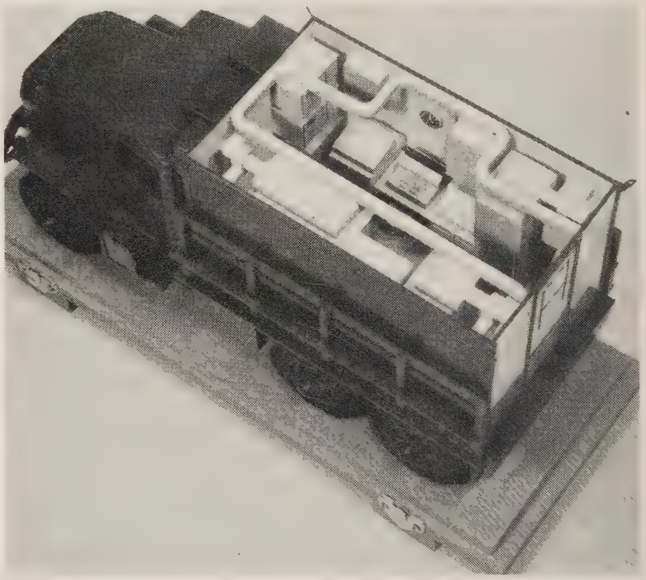

Fig. 2—Typical BASICPAC computer arrangement.

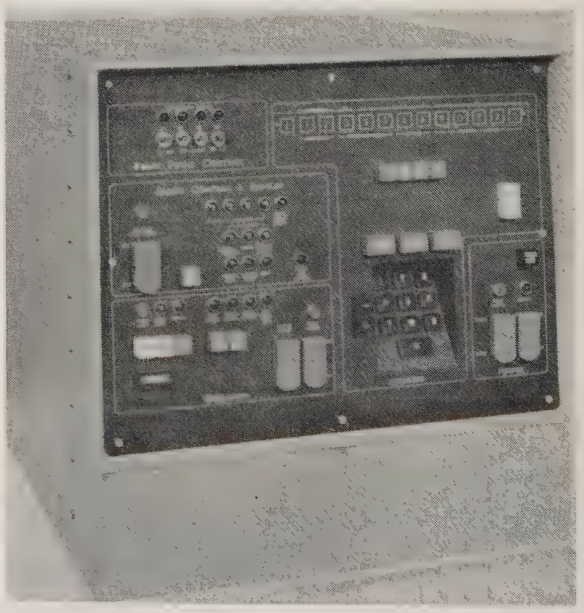

Fig. 3—COMPAC general-purpose control panel.

real-time operations via communications converters and can thus operate in a communications mode with geographically dispersed computers, data sources, and data receivers.

Programming Techniques

The establishment of programming techniques that are suitable for tactical Army purposes provides a real challenge. Digital computers are not the "Big Brains" that script writers and the layman fancy them to be. They are, in fact, rather dull and can do little more than compare two numbers and decide if one is larger than the other. Their ingenuity, accuracy, ability to accept seemingly complex instructions, evaluate and choose alternatives, and provide documented answers are all a reflection of the programs that are written for their step-by-step operations.

To avoid having to ship FIELDATA computers into tactical areas with captive Ph.D.'s preparing and modifying the necessary programs on site, suitable programming techniques are being devised which will permit more reasonable Army talent to perform this task. First, the use of a uniform set of instructions (order code) and a common approach to program writing for all the computers guarantees a maximum transfer-of-training, when personnel are shifted among the computer types. Second, a large set of programming aids is being prepared, including often-used subroutines, mathematical routines and repetitive processing methods. Fixed and/or floating point trigonometric, square root, logarithmic, exponential, double precision, sort-merge, and debugging routines are examples. A library of such aids prepared on and callable from tapes will accompany computers. Third, assembly subroutines and compilers are being devised to simplify the final program preparation and permit the computer to assume part of this drudgery. Fourth, and most important, a vigorous attempt is being made to achieve an automatic programming language. This would permit writing the instructions in a form and language convenient to the programmer and then using a special translation program (one more programming aid) to translate those instructions into a form that the computer can interpret and act on.

As applications are studied and adopted, general programs will be written for them. The execution of program modifications necessitated by specific system configurations and data flow lines should be simplified by the above described programming techniques.

Data Transmission Equipment

The interchange of data between geographically dispersed areas over tactical communication facilities is accomplished by using a family of data terminals now being developed for this purpose. Eight-bit binary characters (units of the FIELDATA code) are the units of transmission. One terminal employs a start-stop mode of operation. It transmits 150 characters (1200 bits) per second over an ordinary tactical voice facility. A second terminal employs a synchronous mode of operation. It transmits 300 characters (2400 bits) per second over an ordinary tactical voice facility. A third terminal also employs a synchronous mode of operation. It transmits 2400 characters (19,200 bits) per second over a tactical carrier facility of 12 voice channel bandwidth.

Data transmission can be accomplished in real time or delayed time. In real time, it is conducted between computers or between computer and data device via communication converters and data terminals. In delayed time it is conducted between external memory devices, such as magnetic tape transports, via suitable buffers and data terminals.

Input-Output Equipment

The development of a sufficient variety of tactical input-output devices for the FIELDATA family proved to be a greater challenge than could be met by the time and resources that could be made available. The great number of information forms in use commercially and potentially suitable for tactical applications, such as cards, paper tapes, magnetic tapes, magnetic cards, printed page, keyboard devices, etc., could not all be investigated and militarized.

In what was considered a reasonable approach, a comprehensive investigation was initiated into the state of the art of input-output devices, and concurrently a development program was undertaken to achieve militarized versions of the patently necessary types. The investigation is complete, and the results are being evaluated. The development program is well under way.

Probably the most important device in this program is the Militarized Magnetic Tape Transport. With a packing density of 300 characters per inch and a speed of 150 inches per second, it has a processing speed of 45,000 FIELDATA characters per second in its function as an external memory for the FIELDATA computers. It uses one-inch-wide Mylar tape and a thirteen-level, redundant, Hamming code which will correct a single-bit error and detect a double-bit error in a FIELDATA character, thus providing a high level of reliability in operation.

Other input-output devices under development are a high speed page printer with a speed of 600 lines (each 120 characters wide) per minute, a keyboard unit associated with a page printer and paper-tape punch and reader, a high speed paper tape reader, and a terminal-type militarized magnetic tape transport for use in delayed-time digital data communications.

Advanced Techniques

The rate of technological advance in the computer field is truly staggering. Every decision made to standardize in any aspect of this dynamic field is a guarantee of obsolescence. To minimize this effect, an effort is made to maintain familiarity with its significant developments and to assist in probing its frontiers.

An attempt to describe these avenues of investigation runs the risk of fantasy. An attempt to keep pace with them seems impossible. Continued microminiaturization of components promises to yield sizes approximating neurons. (What then will be the equivalent synapse connection?) Continued studies in multiple list structures and machine learning processes are pointing to true automata. Thermoplastic-film recording devices will store volumes of data in so many square inches of material. Magnetic thin-film and multi-aperture core devices will permit switching speeds for which the speed of light becomes a limiting factor for reasonable hookup distances.

It is sufficient to say that work in advanced techniques permits the FIELDATA Equipment Program to proceed with imaginative planning but conservative "doing."

Human Factors Studies

The final area to be described in the FIELDATA Equipment Program, that of human factors studies, is considered the most critical for successful tactical usage of ADP. In the man-machine systems contemplated, so much is known about the machines and so little is known about the men who work with them that a considerable mismatch often occurs. Good intentions alone will not solve this problem, however. While much good remains to be done in this field, it is correspondingly a very difficult field in which to do good. For one reason, the amount of money expended in the engineering and scientific community on studies in the behavioral sciences is a pitiful fraction of that expended in the physical sciences. For another, there is little acceptance of, if not hostility to, work in this field.

Nevertheless, an attempt is being made to minimize the man-machine mismatch. Even in the role of equipment designers, knowledge is being gathered on the characteristics and aptitudes of the tactical personnel who are expected to operate this equipment, and the training and indoctrination afforded them. Whenever possible, information is interchanged in these areas of selection, training, and design. The suitability of consoles, keyboards, displays and other man-machine interfaces are carefully analyzed before design acceptance. The proper degree of automatization, *i.e.*, task sharing between man and machine, is studied. Methods for psychological preparation of the user to avoid innate hostility to the machine are given delicate (and less than obvious) consideration.

In retrospect, while these efforts have been groping, the results have been rewarding.

Program Status

With the delivery of the first MOBIDIC to USASRDL, Fort Monmouth, N. J., in December, 1959, *on schedule*, the FIELDATA Equipment Program has reached the stage of testing its system concepts and evaluating its equipment merits. Acceptance and evaluation tests have just begun, with good results to date. The fact, however, that this large-capacity computer installation rolled the highways from factory to Fort Monmouth and then worked when "plugged in" is, in itself, indicative of one concept-mobility.

In recent months, another challenge was posed for this program. The Signal Corps was assigned a "crash" program for the design, construction and delivery *in this calendar year* of a MOBIDIC especially arranged for a large scale logistics application of the Seventh U. S. Army in Europe. The total Signal Corps role includes equipment design and fabrication, system analysis and programming, troop training and initial system operation.

The logistics application concerns stock control of maintenance and spare parts for the Seventh Army. It is of surprising magnitude for a field army. The list of maintenance and spare parts includes about 200,000 types. Approximately 18,000 daily transactions are involved relating to the logistics flow in over 100 depots, stock control points, direct supply units, etc. Seventh Army stock control for this class of supplies is now being handled at a central point by a combination of electrical accounting machines and a fixed type computer. The fixed-in-concrete nature of this arrangement and the three-day cycle time required are inappropriate to a field army function. The MOBIDIC already in fabrication for this assignment is expected to accomplish the same stock control function in a ten-hour cycle. It will also be a mobile unit, capable of moving with the field army at a moment's notice, and prepared to take up its assignment as soon as it arrived at its new location. It could also take over assignments intended for any other FIELDATA computer, just so long as a program is available for this other assignment. This backup capability is a most important characteristic of FIELDATA computers.

The Future

The success of ADP in general, and FIELDATA equipment in particular, for tactical applications, has yet to be established. It will depend on many things, some of the more obvious being whether the equipment works well and whether the system concepts are valid. But most important will be the degree of user acceptance. Will the user adjust his procedures to the ADP methods; will the user accept the ADP output (or will he, figuratively speaking, check the slide rule by long division) or will the user feel crowded out by, or in competition with, the ADP equipment? It is hoped that good equipment performance will win over the user and overcome the type of adverse reactions that have been experienced all too frequently in commerce and industry with the introduction of ADP methods.

A Four-Wire Electronic Automatic Communication Switching System for a Field Army*

G. W. BARTLE,† T. A. PFEIFFER,‡ AND S. B. WEINER§

Fig. 1.

Summary—**Plans for a new communication network, for a military theater of operations, have been under consideration since the end of World War II. It is axiomatic that a common user communication system, in which channels of communication are shared among a large number of users, must provide means whereby these channels are used with a maximum efficiency. In such a system, efficiency of operation depends to a large extent on the rapidity with which a large volume of communication traffic can be switched throughout the network, with a minimum of time being expended in setting up and taking down numerous connections.**

This article recounts the history of the development of a communication channel switching system as dictated by changing military requirements, accenting wide dispersal and mobility and the effect of this system concept on the design of military communication switching equipment. Early efforts to improve manually operated switchboards are described, with the aim of making clear the logical sequence of ideas leading to the development of the military four-wire automatic electronic switching system, now nearing completion. This automatic system is described in some detail as to its operating characteristics, and the reasoning behind the equipment design is discussed. The organized program to insure reliability of operation carried on concurrently with the equipment development is outlined and results described. Finally, the shape of things to come in military electronics switching equipment, as a logical next step from the point where it now stands, is prognosticated.

* Received by the PGMIL, July 11, 1960.

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THE U. S. Army Signal Corps is developing and building a four-wire mobile automatic electronic-communications-switching system to serve the army in the field. The work is being performed jointly by the U. S. Army Signal Research and Development Laboratory, Stromberg-Carlson Division of General Dynamics, and the Kellogg Switchboard and Supply Company, a division of IT & T. This work will result in one of the most modern systems that the present "state of the art" will permit, completely engineered for large-scale production, maximum reliability and flexibility. Switching equipment and compatible telephone station equipment, in sufficient quantity to conduct extensive field tests, will be available by mid-1961.

Before proceeding with the description of the equipment, let us briefly examine the whys and wherefores of a communications-switching system, and the events which led up to the decision on the part of the Signal Corps to develop this particular system.

First, what is a communications-switching system, and why is it necessary? It may be defined as a system which will interconnect *transmission paths in* response to instructions from the users of the system, so that intelligence can be exchanged between humans and/or machines.

In the early days, communication needs were met by connecting individuals directly. (See Fig. 2.) As the number of individuals requiring communication services grew, it became evident that a method had to be devised for building a system such that every user could communicate with every other user *at will*. It was evident that such a system could not be built around the idea of connecting every user with every other user directly. This is illustrated by Figs. 2 and 3. Hence, by necessity, a communication network was evolved, covering a large area and serving a large number of users, in which a user could be switched to any other user and connected via the communication channels constituting the network. From this concept has grown the modern communications-switching systems implemented with highly efficient electromechanical automatic switching equipment.

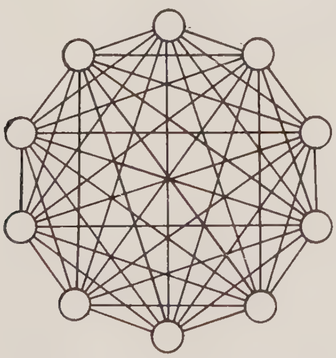

Fig. 2—Point-to-point connection plan: 45 circuits required.

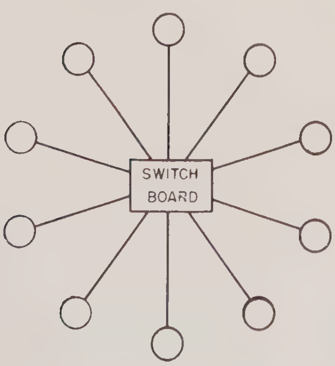

Fig. 3—Switchboard plan: 10 circuits and 1 switching central required.

Now let us review briefly the history of the development of tactical switching equipment for use by the Army. During World War II, the switching facilities used by the field army were adaptations of manually operated civilian switchboards which were designed using techniques developed in the early part of the century. Hand-operated *signaling* generators were used to signal over trunk connections between switchboards, and the operators of these switchboards had to monitor all established connections to determine when such connections could be broken down. At the close of the war, it was apparent to those responsible for maintaining tactical military communications systems that this type of switching equipment was inadequate for the job. Expensive and scarce communication channels were being used inefficiently, and a large number of men were required to operate the switching equipment. Therefore, an effort was begun to improve military switching equipment. The first step was an attempt through equipment design to increase the efficiency of manual switchboard operation. Everything was done to reduce the work load of the switchboard operators. This program culminated in the building of the relatively sophisticated switching equipment which is being used by the field army today.

However, two developments have occurred, the appearance of nuclear weapons and the development of electronic solid-state devices, which have made the improved manually operated switching system obsolete and, as a result, have affected the present and future course of military switching apparatus development. A tactical army waging nuclear warfare must be mobile and widely dispersed because of the tremendous destructive power of nuclear weapons. At the same time, tight command control is more than ever essential. It is evident, therefore, that an army waging nuclear warfare requires a flexible, reliable, and fast method of disseminating vital information throughout the organization. In short, the modern army is a large complex organism requiring a nervous system of a high order. This nervous system is its communications plexus. The system's ability to react to change is dependent on the efficiency of the switching apparatus used to implement the system. Manually operated switching equipment is too slow, since it is dependent on the reaction time of the human being.

What, then, is the best way of building a communication system with a fast reaction time? As so often happens, history offers valuable information which is helpful in solving contemporary problems. The area-coverage switching system developed over the years to serve world-wide civilian needs also appears to be applicable to a military tactical situation, since it meets the requirements for flexibility and reliability. Providing that such a system can be implemented with high-speed, compact, automatic-switching equipment, the additional military requirements for mobility and fast reaction time can also be met. Solid-state electronic device circuitry applied to communications switching equipment

design offers a method of obtaining switching equipment with these characteristics.

Now, what might a tactical military area-coverage switching system look like? One version of such a system is illustrated by Fig. 4. The nodes of the grid designated "13" are electronic automatic long-distance trunk switching exchanges, carrying the official nomenclature of Electronic Telephone Central Office AN/TTC-13. The squares designated "12" and the circles designated "14" are local electronic automatic switching exchanges with facilities for terminating telephone lines and also trunks for connecting to the long-distance network and to other exchanges. In the official nomenclature, these exchanges are Electronic Telephone Central Offices AN/TTC-12 and 14. Operationally, these exchanges differ only in size. The AN/TTC-12 will accommodate 200 lines and 80 trunks, whereas the AN/TTC-14 will accommodate a maximum of 60 lines and 16 trunks. The triangles designated "15" are electronic automatic trunk-switching exchanges carrying the official nomenclature Electronic Telephone Central Office AN/TTC-15. Its use is depicted in the triangular network which shows an intermediate or "tandem" arrangement between the long-distance grid and several local electronic automatic exchanges. The telephone instrument shown in the figure is Telephone Set TA-341/PT. It is designed especially for use with the automatic electronic switching equipment. Communication channels between switching centers will be obtained primarily through the use of radio relay equipment and associated multiplex equipment, although if the situation is stable enough, cable and carrier equipment may be used. Switching centers will be moved from place to place, as the military situation dictates.

Under the direction of a user, the system will function as follows: (refer to Fig. 4). By removing the hand set of the calling telephone from the cradle, connection is made automatically to the local Electronic Telephone

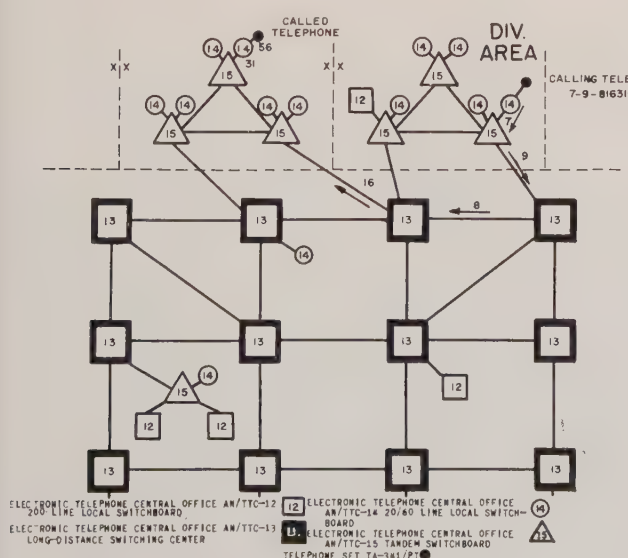

Fig. 4—Army area communication system.

Central Office AN/TTC-14. The user inserts the numbers, shown on the figure, into the system by manipulating the key set of the telephone. The digit "7" causes the AN/TTC-14 to extend the call to the "tandem" network. The digit "9" causes the Tandem Central Office AN/TTC-15 of the tandem network to extend the call to the Central Office AN/TTC-13 of the long-distance network. At this point, the user, by keying the number "00," can call in the long-distance central office attendant to complete the call for him if he does not have access to the system-directory information. The connection shown in the figure, however, has been completed by the user without operator assistance. The digit "8" extends the call to the next long-distance central office, and the number "16" designating the called "tandem" network extends the call to a Central Office AN/TTC-15 of that network. The "tandem" network functions as one switching center. When the call arrives at the AN/TTC-15 connected to the long-distance network, it is automatically routed to the AN/TTC-15 serving the called local central office. Therefore, when the signals representing the number "31," the number which designates the called local central office, arrives at Central Office AN/TTC-15, they are automatically retransmitted to the Central Office AN/TTC-15 serving local central office number "31." The number "56" causes the inward-local central office to signal the called telephone number "56."

At this point, it may be appropriate to describe the switching and telephone equipment of the system and to describe some of its operational characteristics.

Electronic Telephone Central Office AN/TTC-12

The AN/TTC-12 provides complete communication facilities as a 200-line local switchboard for use at large headquarters. The equipment is installed in a transportable shelter normally mounted on a $2\frac{1}{2}$-ton truck. Included in the shelter is one operator's position, four switching equipment cabinets, one transmission equipment cabinet, a main distribution frame, power supply, and an ac power distribution panel. Also included in the shelter are air conditioners, a heater, test equipment, fans and blowers, tools, storage compartments, and a bulletin board. The facilities provided by this central office are:

1) 200 subscriber lines.
2) 30 trunks to a long-distance-switching center (AN/TTC-13).
3) 50 trunks to other local and tandem central offices. These trunks can be divided into as many as six groups with a maximum of 50 trunks in a group.
4) 1 operator's position from which information can be supplied to subscribers, and assistance rendered in completing incoming calls.
5) 60 simultaneous calls can be in progress at one time.

Technical Characteristics

Operating temperature range	$-40°$ to $+149°$F
Transmission bandwidth through the central office	250 to 4500 cps ± 1 db with respect to 1000 cps
Insertion loss (line to line, trunk to trunk)	0 db ± 0.5 db with respect to reference level
Input impedance	600 ohms ± 10 per cent between 300 and 3500 cps at a phase angle of less than 30°
Operating voltage requirements	$\left.\begin{matrix}+12\text{ v}\\-12\text{ v}\end{matrix}\right\}$dc
Power consumption	1200 watts approximately
Primary source of power	110 v, 50/60 cps single phase
Shelter size	$81''$ high $\times 141''$ long $\times 83''$ wide

Electronic Telephone Central Office AN/TTC-13

The AN/TTC-13 is a trunk switching center used to implement the long-distance trunk network. It is also provided with trunks to tandem and local central offices. The equipment is installed in a transportable shelter. The apparatus is similar to that housed in the shelter for the AN/TTC-12 (local switchboard), except that it has two operator's positions. The facilities provided by this central office are:

1) 100 trunks to other long-distance switchboards. These trunks can be divided into as many as 8 groups with a maximum of 100 trunks in a group.
2) 60 trunks to local and tandem switchboards. These trunks can be divided into as many as 10 groups with a maximum of 60 trunks in a group.
3) 2 operator's positions for rendering assistance in completing calls as required.
4) 80 simultaneous calls can be in progress at one time.

Technical Characteristics

Operating temperature range	$-40°$ to $+149°$F
Transmission bandwidth through the central office	250 to 4500 cps ± 1 db with respect to 1000 cps
Insertion loss (line to line, trunk to trunk)	0 db ± 0.5 db with respect to reference level
Input impedance	600 ohms ± 10 per cent between 300 to 3500 cps at a phase angle of less than 30°
Operating voltage requirements	$\left.\begin{matrix}+12\text{ v}\\-12\text{ v}\end{matrix}\right\}$dc
Power consumption	1300 watts approximately
Primary source of power	110 v, 50/60 cps single phase
Shelter size	$81''$ high $\times 141''$ long $\times 83''$ wide

Electronic Telephone Central Office AN/TTC-14

The AN/TTC-14 is made up of three different units and power supply. The basic unit contains 20 local lines and 8 trunks. Each auxiliary unit contains 20 lines and 4 trunks. One or two auxiliary units may be attached to the basic unit. The third unit consists of an operator's position. Each unit is packaged for outdoor use and is capable of withstanding shock and vibration tests. This switching equipment will most often be mounted in a jeep trailer or in a small shelter and is intended to serve primarily the units of an army division. See Fig. 5. The facilities provided by this central office are:

1) 20, 40, or 60 subscriber lines
2) 8, 12, or 16 trunks to other locals, tandems or long-distance switching centers. These trunks can be divided into 4 groups with a maximum of 16 trunks in a group.
3) 1 operator's position for which information can be supplied to subscribers and assistance rendered in completing incoming calls.
4) 9, 16, or 23 simultaneous calls can be in progress at one time.

Technical Characteristics

Operating temperature	$-40°$F to 125°F
Transmission bandwidth through central office	100 to 60,000 cps $+1$ db with respect to 1000 cps
Insertion loss (line to line, trunk to trunk)	1.5 db ± 0.5 db with respect to reference level
Input impedance	600 ohms ± 10 per cent between 300 and 3500 cps at a phase angle of less than 30°
Operating voltages	$\left.\begin{matrix}+12\text{ v}\\-12\text{ v}\end{matrix}\right\}$dc
Power consumption	500 watts (max.)
Primary source of power	110/220 volts; 50/60 cps single phase
Case sizes	basic unit: $17\frac{3}{4}''\times 44''\times 17\frac{1}{2}''$ auxiliary unit: $17\frac{3}{4}''\times 44''\times 17\frac{1}{2}''$ operator's unit: $11\frac{1}{2}''\times 20''\times 16\frac{1}{2}''$ power supply: $17\frac{3}{4}''\times 15\frac{1}{2}''\times 15''$

Electronic Telephone Central Office AN/TTC-15

The AN/TTC-15 is a central office that has trunks to other tandem central offices, to long-distance central offices, and to local central offices. It is used to provide a switchable trunk network for an army division. The equipment is installed in a transportable shelter. The apparatus is similar to that housed in the shelters for the AN/TTC-12 and AN/TTC-13. Like the AN/TTC-12, it has one operator's position. The AN/TTC-15 tandem central office will normally be provided in groups of three, and the facilities are:

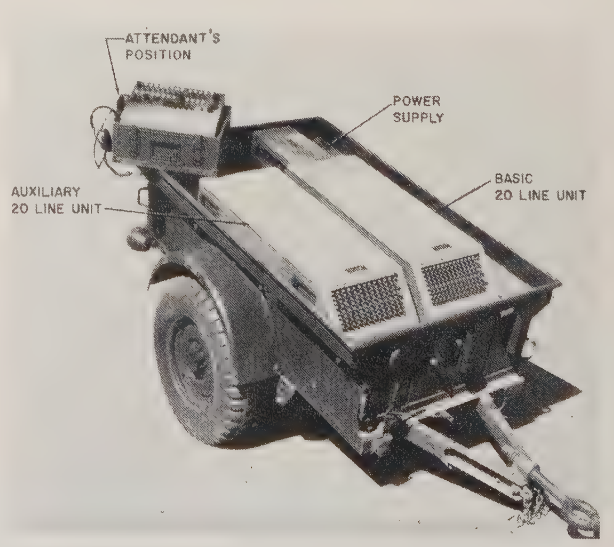

Fig. 5—Electronic Telephone Central Office AN/TTC-14: 40-line version mounted in a $\frac{1}{4}$ ton trailer.

1) 48 trunks to other tandem central offices divided into two groups, with as many as 24 trunks in a group.
2) 18 trunks to long-distance central offices.
3) 72 trunks to local central exchanges divided into 20 groups, with a maximum of 72 trunks in any one group.
4) 1 operator's position for information and rendering assistance in completing calls as required.
5) 70 simultaneous calls can be in progress at one time. Automatic rerouting facilities are provided.

Technical Characteristics

Operating temperature range	$-40°$ to $+149°$F
Transmission bandwidth through the central office	250 to 4500 cps ± 1 db with respect to 1000 cps
Insertion loss (line to line, trunk to trunk)	0 db ± 0.5 db with respect to reference level
Input impedance	600 ohms ± 10 per cent between 300 to 3500 cps at a phase angle of less than 30°
Operating voltage requirements	$\left.\begin{matrix}+12\text{ v}\\-12\text{ v}\end{matrix}\right\}$dc
Power consumption	1200 watts approximately
Primary source of power	110 v, 50/60 cps single phase
Shelter size	81″ high × 141″ long × 83″ wide

Telephone Set TA-341/PT

A new four-wire telephone instrument designed for field use has been developed for use with the four-wire electronic switching equipment. It is designated Telephone Set TA-341/PT. (See Fig. 6.) Built-in transistor oscillators, operating from six dry-cell batteries, furnish the voice-frequency supervisory and digit signals for controlling the electronic automatic switching equipment. Voice-frequency signals from the switchboard trigger a transistor oscillator which feeds a voice-frequency tone into the receiver transducer. The output of the transducer feeds into an acoustic amplifying chamber, and the resulting signal constitutes the "ringing" tone. A key set serves in place of a dial. All circuits are "plug-in" modules incapsulated to protect them from dust and moisture. A variable amplifier on the receiver circuit is used to control the volume of the incoming voice signals. The volume of the "ringing" tone can also be controlled. Telephone Set TA-341/PT can also be used independently of the switching system on a point-to-point basis over wire circuits or radio channels. DC signalling is used on "point-to-point" wire connections. AC signalling is used on "point-to-point" radio connections.

Technical Characteristics

Power supply	6 "C"-size dry-cell batteries (BA-42)
Operating temperature range	$-40°$F to $+149°$F
Transmission bandwidth	300 to 3500 cps
Ringing level	80 db RAP at 3 feet
Output-transmission levels	-9 dbm nominal voice–4 dbm nominal-compound-signaling tone
Size	$3\frac{3}{4}''$ high $\times 9\frac{1}{8}''$ long $\times 10\frac{5}{8}''$ wide
Weight	$10\frac{1}{2}$ lbs.
Material	Glass filled polyester

Figs. 7 and 8 are typical illustrations of the AN/TTC-12, -13, and -15. Figs. 9 and 10 (next page) show drawer and component assemblies typical of these three central offices.

In all of these central offices, maximum use has been made of solid-state electronic devices to obtain switching speed and compact units. To further reduce size and weight of the larger central offices, time division multiplexing techniques have been used, instead of the conventional crosspoint matrix.

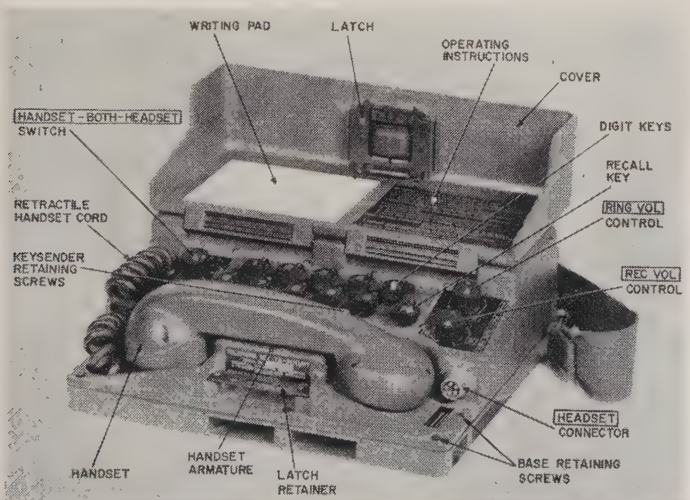

Fig. 6.

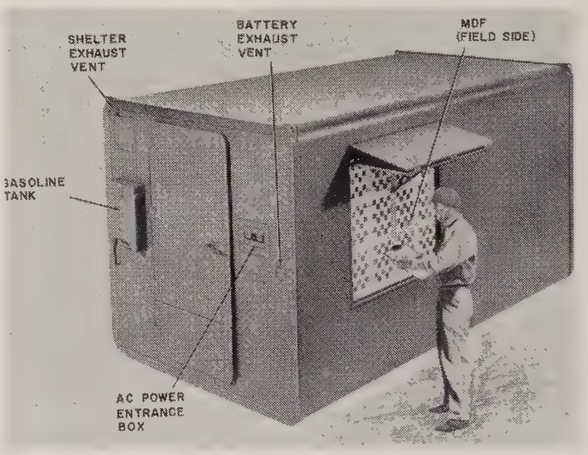

Fig. 7.

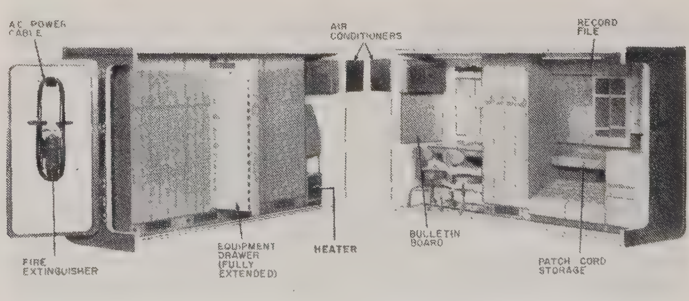

Fig. 8—Central office, telephone, electronic, overall internal view.

The signalling and supervisory frequencies employed in the system are shown in Fig. 11. Voice-frequency control signals eliminate the necessity for using signal converters when transmitting over radio channels.

Long-distance Central Offices (AN/TTC-13) and tandem Central Offices (AN/TTC-15), when forwarding a series of controlling signals in the process of establishing connections to other central offices in the system, request acknowledgment of each signal from the receiving central office before sending the next succeeding signal. This is "interlocked" signalling and is shown in Fig. 11 in the columns headed "Acknowledge Local" and "Acknowledge Long Distance and Tandem." This interlock feature insures that the correct signal will be received at the distant central office, even under poor radio transmission conditions.

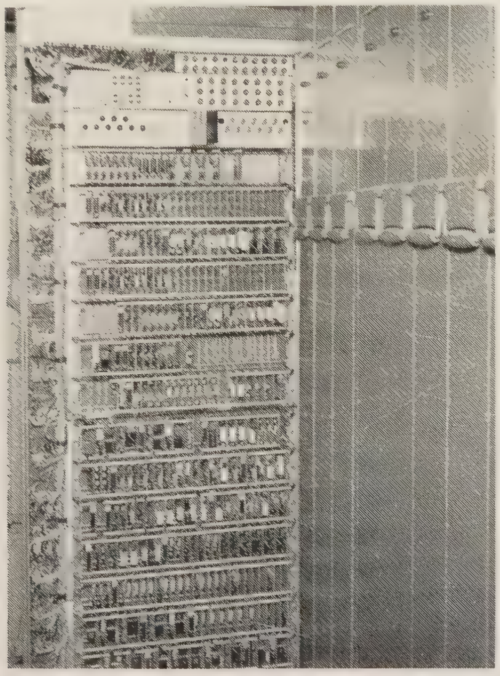

Fig. 9.

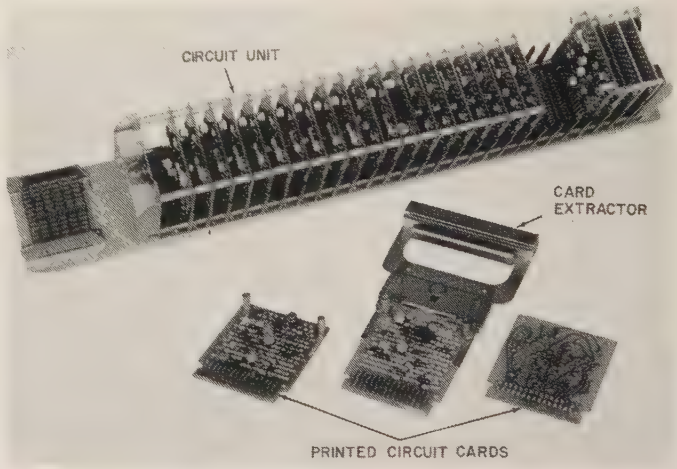

Fig. 10.

Signal Frequencies and Codes

$S=1700$ cps
$U=1900$ cps
$V=2100$ cps
$W=2300$ cps
$X=2500$ cps
$Y=2700$ cps
$Z=2900$ cps

Dial Tone $=600$ cps steady (distorted)
Ring Signal $=600$ cps interrupted 1 second on 2 seconds off
Ring Tone as for ring signal
Busy Tone (line) 600 cps $\frac{1}{2}$ second on $\frac{1}{2}$ second off
Busy tone (truck) 600 cps $\frac{1}{4}$ second on $\frac{1}{4}$ second off

Signal	*Code*	*Acknowledge Local*	*Acknowledge L.D. and Tandem*
digit 1	*VW*	*VW*	*VW*
digit 2	*XW*	*XW*	*XW*
digit 3	*UY*	*UY*	*UY*
digit 4	*UV*	*UV*	*UV*
digit 5	*XY*	*XY* when acknowledge request	*XY*
digit 6	*WY*	*WY* has been received.	*WY*
digit 7	*VX*	*VX*	*VX*
digit 8	*UW*	*UW*	*UW*
digit 9	*VY*	*VY*	*VY*
digit 10	*UX*	*UX*	*UX*
seize	*S*	D. T.	*Z*
release	*YZ*	Nil	Nil
recall	*WZ*	Nil	Nil
ring trip	*S*	Nil	Nil
ring signal	600 cps	*S* (from telephone)	Nil
acknowledge request	*VZ*	*Z*	Nil
cancel	*UZ*	Nil	Nil
spares	*XZ* (*SU SV SW SX SY SZ*)	—	—

Signal level from switchboards shall be -18 ± 1 dbm per frequency. Frequency tolerance, S through Z ±20 cps, 600—cps ±25 c/s. Signal will persist until acknowledged. Ringing signal 0 ± 1 dbm. (Nom.)

Signal level from telephones shall not exceed -3 dbm with either single-frequency or compound signals. Frequency tolerance ±20 cps. Minimum duration 50 Ms. (Nom. -4 dbm.)

Signal detection circuits in switchboards shall operate to an input range of 0 to -28 dbm. Frequency tolerance U through Z ±30 cps, 600 cps ±10 per cent.

Fig. 11.

Returning to consideration of the fact that the switching system we have been describing is completely four-wire, let us answer the question—Why four-wire? Recalling that the military area-coverage system is made up of many interconnected switching centers, and that connections through such a system will involve a large number of these switching centers connected in series, the first obvious advantage of employing four-wire switching facilities is improved transmission. All of the equipment—radio relay equipment, carrier equipment, etc.—used to implement present military communications system is four-wire or the equivalent, except the switchboards and the telephones which are two-wire. This requires that all interconnecting trunk circuits between present switchboards be converted to two-wire at the switchboards through hybrid coils. This introduces loss and complicates the maintenance of proper transmission levels and singing margins on carrier-derived trunks. Use of four-wire switching equipment eliminates the hybrids and the disadvantages inherent in their use.

Four-wire switchboard subscriber-line circuits, designed to operate on voice-frequency signals, make it possible to connect full duplex subscriber radio sets directly into the four-wire switchboards, without using hybrids or signal converters. The absence of hybrids on this type connection also means that the signal level can be kept high without causing a singing condition. This is advantageous on a noisy radio circuit.

Considering the telephone, it is obvious that it would be illogical to use two-wire telephones with four-wire switchboard line circuits, since to do so would require the use of hybrids and complicate design problems involved in utilizing voice-frequency signalling on the lines.

The transmission of data in military communications system is increasing. Error-free data transmission is a necessity and is easily accomplished in a four-wire system, because the data transmission is in one direction only, and the return path may be utilized for error checking and correcting. All facts considered, the answer to the question—"Why four-wire?"—is clear.

The statement was made earlier in this article that manual switching is too slow to serve a military area-coverage communication system. What is this manual switching speed, and how does it compare with that attained through the use of electronic automatic switching equipment? A well-trained manual telephone switchboard operator can meet a 10-second answering time on the average under good conditions. Less well-trained operators, functioning under the stress of adverse conditions and heavy military traffic, will be much slower. Considering this fact, and considering that additional time will be consumed by the user in instructing the operator, it is not unreasonable to assume that from 20 to 30 seconds will be required to establish a connection at each switchboard.

The electronic automatic central offices will, on the average, establish a connection at each switching point in $\frac{1}{2}$ second. Disconnect time in the electronic system is relatively instantaneous, whereas in the present manual system, the operators at each switching point involved must perform a disconnect operation. Speed of disconnect is directly related to the efficiency with which expensive trunk circuits can be used. Speed of disconnect reduces the amount of time that valuable transmission facilities are needlessly held up.

We have said that maximum use has been made of solid-state electronic components in the design of the switching apparatus to achieve switching speeds and size reduction. We have compared the operational speed of a manual switching system with an automatic electronic switching system to the marked advantage of the electronic automatic system.

Now let us take a closer look at what is being done to achieve size reduction and reliability. First, what about size reduction? It is a fact that Electronic Telephone Central Offices AN/TTC-12, -13 and -15, the largest central offices in the system, can be transported on a $2\frac{1}{2}$-ton army truck. If a central office of the same capacity and operating characteristics of the AN/TTC-12, for example, were built using relays or electromechanical stepping switches, it is very doubtful that it could be fitted into a 30-foot-long trailer van. An even more startling picture is obtained in comparing a manual switching system with an electronic automatic switching system. See Figs. 12 and 13. This comparison is based on assessing the effects of an identical traffic load applied to both systems.

Next, considering reliability, will we achieve a significant increase through the use of electronic automatic switching equipment? It will be recalled that a military area-coverage communications system is considered to be practicable *only* if it can be implemented with high-speed electronic automatic switching equipment. First, let us show that the electronic switching equipment described earlier is reliable. An extensive program has been carried out to establish a method for choosing reliable circuit components. The circuitry was designed and tested to work within the expected "end-of-life" characteristics of these components. Standby circuitry has been provided so that, in case of a failure of common equipment, operation will not be impaired. A statistical analysis of the data accumulated during the reliability program has indicated the "mean-time-between failures" of components, which will affect 25 per cent of the electronic central office, will be greater than 150 days. Built-in automatic fault-finding equipment with visual alarms and preventative routining equipment makes possible the quick detection and location of trouble. Circuits are built in modular form. Each module is "plug-in," so that fault modules can be easily replaced by functioning modules. All facts considered, it is confidently expected that the electronic exchanges will be very reliable compared to existing military switching equipment. This being the case, a military area-coverage

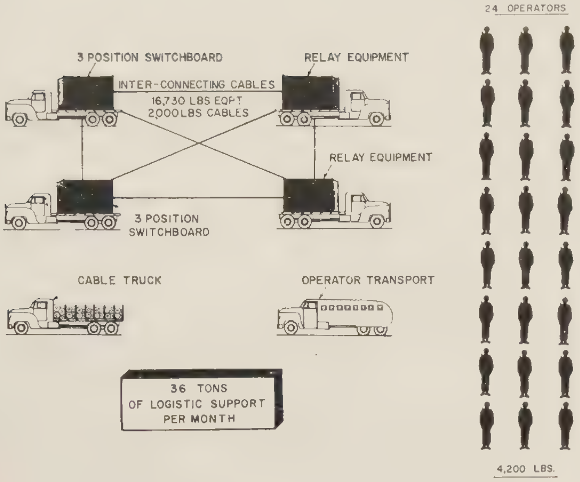

Fig. 12—200-line manual switchboard.

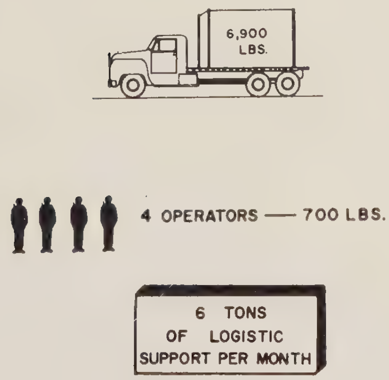

Fig. 13—200-line electronic switchboard.

system *is* practicable. It will provide for system reliability, since adequate alternate routes are provided to insure against transmission failures caused by enemy-inflicted damage to parts of the system, transmission failures on some of the routes resulting from poor radio transmission conditions, or equipment failure in parts of the system. In addition, it will be recalled that to insure proper transmission of control signals the system signaling is interlocking.

It seems reasonable, therefore, to conclude that the use of electronic automatic switching equipment will significantly increase communication reliability.

In conclusion, it may be interesting to look ahead and attempt to predict what future military switching systems might look like. In the system we have been describing, the switchboard operator has not been entirely eliminated. There will be at the long-distance central offices one or possibly two attendants who will be supplied with up-to-the-minute directory information, and who may be called in at the will of the system users to route calls through the system.

Providing that a permanent system directory can be devised, and it is believed that it can be, electronic memories kept up to date from centrally-located intelligence points will provide routing information to the switching equipment. The users will simply insert the necessary address digital information into the system using the key set on the telephone and the call will be routed through the system automatically. Circuits have already been designed to accomplish this.

Future switching equipment will be smaller and lighter, consume less power, and cost less than the presently-available electronic switching equipment. Higher switching speeds, attained through the use of newly-developed electronic devices in future circuit design, will make it possible to reduce the size of switching exchanges without degrading service.

Still further in the future are communications switching systems implemented with equipment which will combine the multiplexing and switching function in a single apparatus. All signals will be translated into a common digital form and transmitted in this form throughout the system. Transmission reliability will be increased, because transmission engineers need cater to only one type of signal. Also, reduction of the logistic support needed for such a system will be significantly less than that needed for existing systems because of its monolithic character.

To the designer of communication switching systems, it is evident that the future holds infinite possibilities for even greater improvements.

Electronically Tunable Circuit Elements*

SAMUEL STIBER†

Summary—**During the past sixty years, attempts have been made to develop electronically-controllable circuit elements to be applied to filter networks in tunable receivers and transmitters. Both the polarization of the dielectric material used in the construction of capacitors and the permeability of the ferrite core material used in inductor design, lend themselves to electronic variation; in fact, the change in the incremental permeability of a magnetizable material in the presence of a superimposed varying magnetic field was patented as early as 1901. Usable circuit elements, however, were not realizable for application in the frequency ranges above 100 kc, nor did the available materials provide the desired characteristics for modern filter design of receivers and transmitters.**

USASRDL initiated a program in 1948 to investigate the problems associated with electronically variable inductances. New ferrite materials were developed and a better understanding of the over-all problem obtained. This program grew in magnitude, calling upon the efforts of both universities and commercial organizations, in addition to the internal effort within this laboratory. The outcome is a family of controllable inductances, electronically tunable in the frequency range dc to 500 Mc with reasonable *Q*'s, power requirements, and small in size and weight. Large frequency variations are obtainable and they are usable under environmental conditions of temperature, humidity and vibration encountered in field conditions. With these electronically tunable inductors the military now have available rereceivers which can be remotely tuned, rapidly scanned over frequently ranges of better than two-to-one and stopped quickly on receipt of a signal. They can sweep large frequency ranges and present a full panoramic display of the signal environment present in each range, together with a simultaneous expanded sector display of the signals of interest.

This paper discusses fundamental considerations and definitions of ferromagnetic, ferroelectric and back-biased devices. It describes the problems involved in the development of the electronically controllable inductance, provides a discussion of requirements this device must meet, and gives operating characteristics of inductors developed. Applications of the device in military equipment are discussed, some examples of their use in receivers described and some typical circuits provided. A comparative evaluation of ferromagnetic, ferroelectric and back-biased diode tuning devices completes this paper.

I. Introduction

THIS PAPER grew out of studies of controllable circuit elements for use in countermeasures panoramic receivers. By panoramic reception is meant the reception of signals within a band of frequencies and the display on a visual indicator of the presence and character of these signals. There are, in general, three methods of panoramic reception: 1) that in which the signal frequencies are swept in succession past a relatively narrow-band selective circuit whose amplified output is used to actuate a visual indicator, 2) that in which the signal frequencies are applied simultaneously to a number of selective circuits of adjacent frequencies and the outputs applied either simultaneously or in rapid succession to a visual indicator, and 3) that in which the selective circuit is moved past the signals.

By countermeasures receivers is meant a receiving system to be used against noncooperative signals. Although countermeasures receivers have much in common with conventional receivers, the signals which they are intended to intercept, being of an unknown character, call for wide RF bandwidths, the utmost in sensitivity, large dynamic range, and a multitude of detector types for equipment economy and high probability of intercept. RF sweep ranges are generally as wide as the state of the art will permit. Rapid scan is often desirable and sometimes it is required that the RF band be scanned within the time duration of a single pulse. In addition to rapidly sweeping wide RF bandwidths, it is often also necessary to scan narrower RF bands, and to position these narrow bands anywhere within the RF band. In addition, particularly for countermeasures applications, electronic tuning permits the sweep of RF frequency to be stopped quickly on receipt of a signal. Thus, the advantages of an auxiliary high speed, multifunction (pulse-width and PRF) signal analyzer can be fully realized by stopping the receiver on the signal of interest without mechanical overshoot. The panoramic receiver is also capable of sweeping the entire signal range, thus presenting a full panoramic display of the signal environment present in that range, together with a simultaneous expanded sector display. A review of the above requirements quickly indicates that tuning elements utilizing mechanical sliding or contacting structures are not acceptable. Rapid rotation of conventional capacitors, butterfly structures, split cylinder filters and capacitive loaded coaxial cavities have all been tried and rejected.[1]

In addition to the above requirements, the ideal tuning element should be capable of operation to 1000 Mc with a usable Q for use in amplifier or oscillator circuits. It should have a low temperature coefficient of frequency from $-40°C$ to $+85°C$. It should be small, compact, and capable of large-scale manufacture with only a small fraction of rejects. It should be capable of frequency scan over a ratio of four to one or better, with relatively small control power and with low voltage.

To meet these requirements, the countermeasures engineers within USASRDL sponsored a study and investigation of methods of tuning, aimed at the above requirements, and a task[2] was placed with the Engineering Research Institute, at the University of Michigan, Ann Arbor. Some of the information contained in this

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

[1] S. Stiber, "Survey of tuning systems in the frequency range above 300 mcs," presented at Symp. on Countermeasures Intercept, LCS 56/1 RDB, pp. 233–262; July 15, 1948.

[2] Task #4. Contract DA-36-039 sc 63203.

paper resulted from this task. In addition, contracts were placed with various commercial organizations for the development of materials, tuning elements and prototype receivers. These firms are listed in Section IV.

II. Definitions and Fundamental Considerations

Ferromagnetic Devices

In the simplest form, the tuning element consists of a ferrite core containing two toroidal windings. The winding to be controlled is called the signal winding and the other is the control winding. By varying the current in the control winding, we change the magnetic field acting on the core material and, in turn, the inductance of the signal winding. The core material in general exhibits a wide variation of permeability with applied field. A class of magnetic ferrospinels or ferrites have enjoyed prominence in this field because of their high resistivity (10^3 to 10^9 ohms/cm) and freedom from eddy current loss.

Ferroelectric Devices

The ferroelectric tuning element is a capacitor whose value can be changed by an applied voltage. In general, the voltage applied to the capacitor plates results in a change in the dielectric constant of the material between the plates. The titanate ceramics may be considered as representative of materials suitable for electronic tuning. For maximum tuning range, materials showing the largest change in ϵ with applied electric field E, are desired. When a large electric field is applied to a ferroelectric material, it is driven into saturation or maximum polarization. In a practical situation, the limit of E is generally determined by the electric breakdown field of the specimen. Unique to ferroelectric tuning is the problem of producing thin sheets of titanate dielectric having apparent homogeneous properties. Local impurities in thin specimens are very noticeable, even tending to produce electric breakdown. The chief difficulty with ferroelectric tuning is that of obtaining large tuning ratios together with low temperature sensitivity.

Back-Biased Diodes

Variable capacitance germanium diode: A semiconductor when biased in the reverse direction (nonconduction) is a capacitance which can be varied by the bias voltage. Giacoletto and O'Connell[3] have described such a diode. The diode consists of a 0.02-inch dot of indium, alloyed on a 0.002-inch-thick wafer of n-type germanium and mounted with low inductance connections.

Typically, the performance with 6-volt bias is as follows: a capacitance of 38 $\mu\mu$f, a capacitive change of 3 $\mu\mu$f per volt, a Q of 17 at 500 Mc. Only microwatts of dc control power are required. Over the useful range of up to 16 volts, the capacity varies inversely with the square root of the bias voltage. A variation of capacity from 160 to 25 $\mu\mu$f was obtained.

Silicon diodes: In the case of a silicon junction diode, the density of charge carriers at the p-n junction (electrons in the n-region and holes in the p-region) is reduced to almost zero as the voltage is applied in the reverse direction across the diode. This region of zero charge density, known as the depletion region, is not merely swept clear of charge carriers but actually widens as the reverse bias is increased. In effect, the two conducting areas appear to act as two metal plates which tend to move further apart with increase in voltage. The plate area and the dielectric constant remain the same. It is important in application that no part of the signal voltage cause the net voltage applied to the junction to become positive. This occurrence is usually avoided by the placing of two back-biased diodes in series opposition across the tank coil.

The ferroelectric mode of operation is extremely different. Barium titanate ($BaTiO_3$) is mixed with a nonferroelectric buffer material such as strontium titanate and becomes a suitable material. The barium titanate is made up of a multitude of tiny particles whose spontaneous dipoles are randomly oriented. The statistical average of the orientations is zero. When a dc bias is applied to the material, some of the dipoles will align themselves in the field, resulting in a decrease in the dielectric constant of the material. As the biasing field is further increased, more and more dipoles are reoriented until saturation is reached. Minimum capacitance occurs when the device has maximum bias applied. Unlike the back-biased diode, the ferroelectric capacitor can be biased either negative or positive. The performance of the diode capacitor shows only a slight dependence upon temperature, whereas that of the ferroelectric is quite sensitive to temperature.

Fig. 1 shows a typical capacity vs voltage curve at 100 Mc for a University of Michigan barium titanate capacitor and also, for comparison, a Hughes back-biased diode.

III. The Development of the Controllable Inductance (Ferromagnetic Tuning)

Requirements

In summary, the ideal controllable inductance should:

1) Have low loss, high resistivity (10^3 to 10^9 ohms/cm).
2) Have zero temperature coefficient of frequency vs temperature from $-50°$C to $+100°$C.
3) Be small, compact, light-weight.
4) Be capable of large-scale manufacture at low cost.
5) Have controllable inductance ratio of 100 to 1 at 10 kc to 4 to 1 at 1000 Mc.
6) Require small control power.
7) Provide a linear sweep with voltage variation.

[3] L. J. Giacoletto and J. O'Connell, *RCA Rev.*, vol. 18, pp. 66–85; March, 1956.

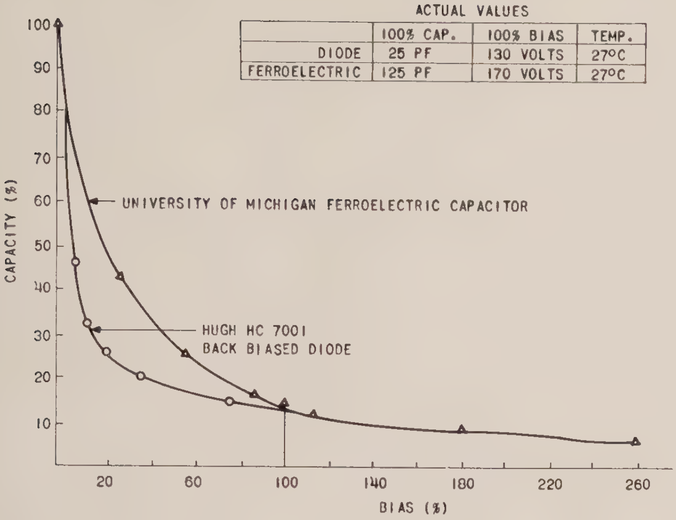

Fig. 1—Typical capacity vs voltage curves at 100 Mc (normalized).

Ferromagnetic Tuning Prior to 1948

de Kramolin[4] described a new tuning device which he said was especially suitable for remote control. Briefly, it consisted of varying the inductance of a tuning coil by changing the permeability of its powdered-iron core. This was accomplished with the aid of an electromagnet, varying the current through its field coil. Fig. 2 illustrates this early tuner. The high-frequency powdered-iron core *m* of low permeability lies between the poles of the outer magnet *E*. The path of the biasing flux is indicated by the arrow *w*. The RF coils are wound in opposite directions on the pressed-powder cup core. Thus, the signal current produced no charge in inductance by its biasing effect. The inductance variation is thus totally a function of the field control winding. It is interesting to note that, at the same time, Siemers and Hulse were experimenting in Berlin with similar configurations for remote electronic tuning. In the period 1941–1945, work in this field was continued in various laboratories in Germany. Approximately five watts was required to produce an inductance variation of nine to one. de Kramolin suggested using a permanent magnet bias to reduce the power requirement. He described an application in which the electronically tuned coil was made the filter element of a TRF receiver.[5]

Fundamental Definition and Considerations

For maximum inductance charge, a large charge in core permeability is desired. Regardless of the initial permeability, it is theoretically possible for us to obtain a permeability approaching unity by driving the specimen into saturation. Therefore, one should look for materials with initial high permeability. The quantity

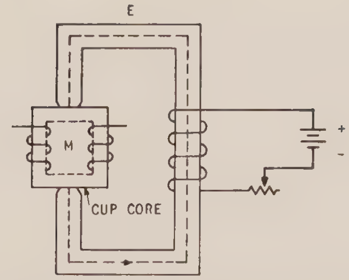

Fig. 2—1938 controllable inductance.

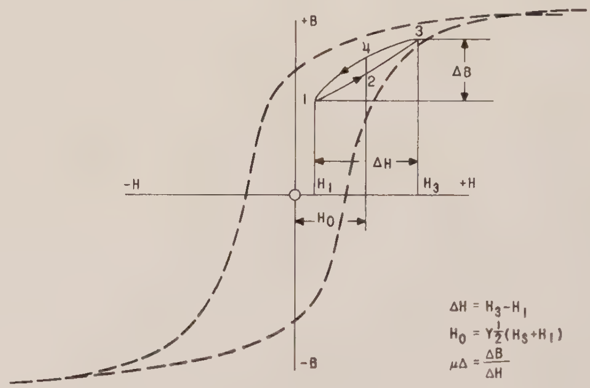

Fig. 3—Definitions of magnetic parameters.

actually concerned in magnetic tuning is the incremental permeability $\mu\Delta$. This is the permeability observed when the specimen is subjected to a combined ac and dc field, both applied in the same direction. This is illustrated in Fig. 3, which gives definitions of magnetic parameters. $\mu\Delta$ changes with both bias field H_0 and ac field ΔH.

Figs. 4 and 5 will further illustrate the definitions which follow.

Initially the flux density rises rapidly as the control current is increased. The rate of increase falls off until saturation of the ferrite is achieved. In the initial stage, there exists a flux density B, which corresponds to a control current i, and at this point the slope of the B-H curve is given by the tangent T_1. Now we apply an ac to the signal winding (whose ampere tunes are small compared to the control winding). The apparent permeability of the ferrite core (that is the signal core) is $\Delta B/\Delta H$ For small values of ΔH, this permeability is very nearly the slope of the tangent T_1 previously defined. The inductance of the signal winding is directly proportional to the incremental permeability $\Delta B/\Delta H$.

If we now apply an increase in control current i_2 we will produce in the ferrite core a second larger flux B_2. Looking at the B-H curve in Fig. 4, it should be noted that the slope T_2 is smaller than T_1. The inductance of the signal winding will have decreased by the ratio of T_2/T_1. As we further increase the control current the slope continues to decrease to T_3, at which point saturation of the ferrite core has been reached and we will have achieved a minimum inductance in our radio frequency or signal winding.

[4] L. de Kramolin, *Wireless World*, vol. 42, pp. 160–162; February 24, 1938.
[5] L. de Kramolin, *Wireless World*, vol. 42, pp. 186–188; March 3, 1938.

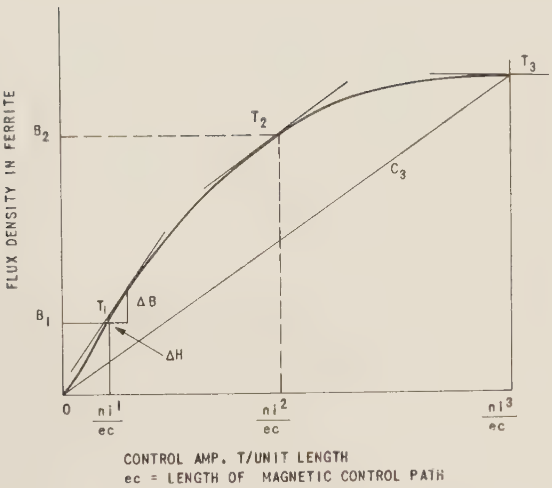

Fig. 4—Incremental permeability tuning showing ideal *B-H* curve for ferrite core.

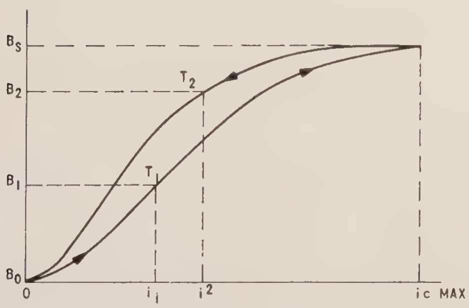

Fig. 5—Effect of hysteresis.

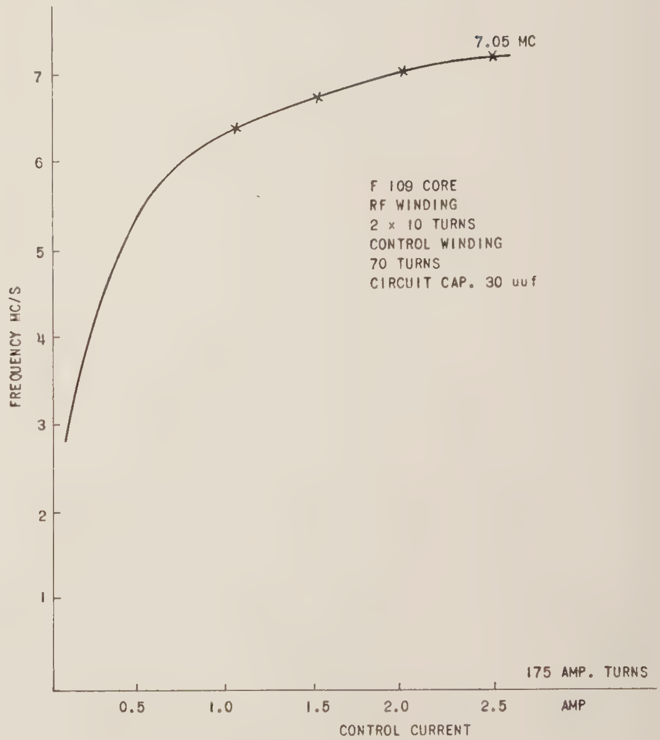

Fig. 6—General Ceramics material *G*.

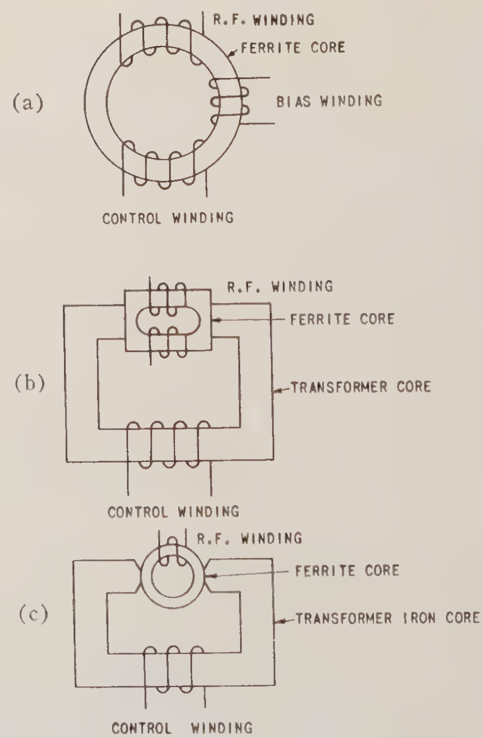

Fig. 7—Typical forms of tuning elements.

The above simplified presentation lacks inclusion of the hysteresis effect. Because of the hysteresis phenomena in the ferrite material, the flux density is not a single function of the control current. The typical behavior of a ferrite is shown in Figs. 5 and 6. Although the hysteresis effect to be described in negligible compared to eddy current losses in the signal region, it plays a very significant part in receiver circuit design.

As the control current is varied, as shown in Fig. 5, from zero to maximum and back to zero, the flux of the ferrite will vary but on the return half-cycle will always be higher than that which corresponded to the same control current on the previous half-cycle. Actually, when the control current is returned to zero, the control flux does not vanish but a residual control flux B remains. For either manual or rapid sweep, it is then necessary to blank out one half of the magnetization cycle (Fig. 7).

Material Considerations

The most important component of the controllable inductor is the magnetic material used in the core winding. Ferrites have been used exclusively. Some of the problems in using ferrites are described below:

1) *Magnetostriction.* At the mechanically resonant frequency, the inductor will experience a severe loss in Q. This condition is present in many low-frequency materials such as Philippe 4E and in Stackpole 1819.

2) *Instability.* When control current is applied it is found that several minutes may be required for the signal winding inductance to stabilize. Examples are Stackpole's Ceramag 7A, Ferricore's C, and in General Ceramics, Q—body material.

3) *Lack of uniformity in core material.* Considerable variability exists among cores of any batch of ferrites. Generally, tracking of such cores is obtained by means of a bias winding in addition to the central winding. Since the core materials vary in initial permeability, the bias currents are adjusted to reduce the initial permeability of the higher permeability cores down to the lowest permeability core in the batch of controllable inductors to be tracked. In order to track at the high end, adjustment must be made of the control winding at or approaching core saturation.

A most desirable procedure is to test each core, demagnetize it, and then measure its permeability and select cores close in initial permeability.

4) *Shielding problems.* It is necessary that capacitive coupling between the signal and control windings be minimized. Capacitive coupling reduces the effective Q of the inductor. A useful solution, particularly at low frequency, is the use of a good electrostatic shield between signal and control windings.

5) *Manufacturing problems.* In addition to obtaining a ferrite core of the desired electrical characteristics, there is the problem of obtaining uniform and consistent properties. Core materials supposedly of the same make-up vary from batch to batch and from month to month. The ferrite manufacturer has a difficult problem in control of raw materials—a small difference in the purity of raw oxides has a profound effect on the variation of product impurities. Even the dust from previous operations which lines the floor influences the make-up of new batches of materials. Matching of cores may require large waste or shrinkage because of elimination of nonusable cores. After proper selection of the core there is the cost of machining, core testing and matching. To this must be added the cost of winding, assembling and final testing.

TABLE I

PERFORMANCE OF FERRITES; CONTROLLABLE REACTORS

Material	Frequency Range, Mc	Ratio	Q	Control Current
Ceramag 27	0.4–6.3	15.7	20	0–50 ma
Ceramag 9	0.75–5.1	6.7	50–100	0–60 ma
Ceramag 5451	9–39–0	4.35	50–80	0–50 ma
Phillips 2285	20–45	2.25	70	0–150 ma
Gen Ceramics Ferramic Q	5–26	5.16	22–46	0–50 ma
MF 2728	35–76	2	35–60	0–30 ma

IV. A LOOK AT THE FUTURE

The story of the development of the controllable inductance, the ferroelectric capacitor and the reverse-bias diode is part of the story of the "fabulous fifties." Contrast de Kramolin's inductor of 1938 with that exhibited at the 1960 IRE International Convention, in New York, by TRAK Electronics Co. (formerly C.G.S.), Wilton, Conn. de Kramolin's device weighed several pounds, and required approximately five watts control power to produce an inductance variation of nine to one in the frequency range up to several hundred kc. Beyond this frequency, its losses became excessive. The C.G.S. No. 81 AMI inductor can be tuned electronically over a 64 to one inductance range, from 50 to 400 Mc. It requires only mils of control current, weighs a few ounces, and is lost behind your thumb. Such devices are in use in missiles, telemetry and in general VHF and UHF low-power applications. Signal windings can handle up to eight watts; however, additional increductor units capable of handling several hundred watts at frequencies between 50 and 100 Mc have been constructed.

Successes with ferroelectrics have been somewhat marginal, particularly because presently available materials appear to dissipate too much energy for application to microwave frequencies. A more thorough understanding of the loss mechanism for these substances is required. Stanford University has an effort underway in their Electronics Laboratory at Palo Alto, Calif. on a new capacitor which has a significantly greater range of capacitance variation. It is called the M-O-S, or metal-oxide-silicon, capacitor. The M-O-S capacitor gets its extended range by going to higher capacitance per unit area at low voltage. This results from the fact that in the M-O-S capacitor the zero bias capacitance is determined by the thickness of the oxide, which in practice can be made of the magnitude of a hundred angstroms, while the zero-bias capacitance of the p-n junction is determined by the inherent width of the depletion layer, which may be of the order of several thousand angstroms.

The 1960–1970 period should see a considerable increase in system utilization of all of these devices to provide remote control, electronic tuning, rapid frequency scan, etc.

Commercial organizations in the 1950–1960 period received support in these fields, mainly from government agencies. The Signal Corps at Fort Monmouth, N. J., has been particularly active in the support of the controllable inductance for use in electronic warfare equipments. Commercial organizations most active have been TRAK Electronics Company (formerly C.G.S. Laboratories); A.R.F. Products, Inc., River Forest, Ill. Vari-L Company, Inc., Stamford, Conn.; and General Ceramics Corporation, Keasbey, N. J.

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The Signal Corps' Contribution to the Microwave Antenna Art*

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Summary—**This paper contains a brief summary of the Signal Corps' contribution to the antenna art. Emphasis is on the post World War II period and on microwave antennas. Only developments which have had reasonably wide application are discussed.**

THE popular image conjured up by the term "antenna" has undergone a rather dramatic revision since the days of the founding of the Signal Corps. At that time an antenna meant an appendage to an insect's head and, indeed, the wagging of the signal flags which was among the more reliable means of communication in those days was somewhat reminiscent of the vibrations of the insect's antennas which, our entomologist friends tell us, are used for a variety of purposes from food-finding to courtship in the insect world.

During the early days of radio communication, while the elders among us were wreaking havoc with interior decorating schemes by stringing long wires through the house, or attaching wires to bedsprings in order to improve the reception on our crystal detector sets, Signal Corps personnel and their colleagues in the communications industry were constructing bigger and better towers and rhombics in order to improve the quantity and quality of messages that could be transmitted by radio. With the advent of radar and the increasing use of higher frequencies, the trend and tempo of antenna developments changed markedly. Radar required relatively narrow beams at VHF and UHF frequencies, thus leading to the development of fairly complex broadside arrays of radiating elements.

The standard search radar set of pre-World War II and early war years was the SCR-270, whose antenna of 32 dipoles became a landmark familiar to many a G.I. Broadside array construction of that period reached a culmination in the "Diana" Radar located at the Evans Signal Laboratory which, in early 1946, electrified the world with the news of radar contact with the moon. The antenna to launch the wave that first made contact with an extra-terrestrial object consisted of 64 dipoles and provided for that time, a phenomenal gain of 21 db in the mid-VHF region. Fig. 1 is a photograph of this antenna.

With the opening up of the microwave region, the entire field of microwave optics was available for exploitation. At these high frequencies, conventional antennas

* Received by the FGMIL, July 11, 1960.
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involving current-carrying conductors were replaced with aperture-type antennas. Indeed, many microwave antennas were more reminiscent of optical devices than anything resembling standard radio frequency equipment. One of the fields in which the Signal Corps was prominent was the adaptation of lens techniques to microwave antennas. The shaped waveguide lens had been demonstrated by Dr. Winston Kock of the Bell Telephone Laboratories to be a component which was readily adaptable to the formation of the narrow beams that were required in microwave radars. The theory of operation was essentially similar to that of the optical lens, with the exception that since the refractive index of the waveguide medium is less than that of light, converging beams are formed by concave surfaces rather than convex. It is believed that one of the first waveguide lenses to be used in a military application was that on the Mortar Locator AN/TPQ-2. Although it proved eminently successful, the end of the war and the somewhat unfortunate choice of the wavelength of 1.25 cm caused the demise of the project. However, the waveguide lens has been used very successfully in a number of other applications, and has achieved a secure place in the antenna field. A typical cylindrical waveguide lens antenna is shown in Fig. 2.

Still another microwave optical device that lends itself to antenna applications is the Luneberg lens. Early in the war it had been shown by Dr. Luneberg that if a dielectric sphere could be made to have a particular radial variation of refractive index, this sphere would act as a lens with one focus on the surface and the other focus at infinity. Due to the spherical symmetry of the structure, if the focal point were moved to any point on the surface, a perfectly collimated beam would emerge diametrically opposite. Although theoretically attractive, practical difficulties in achieving the required radial variation of refractive index for some time prevented this idea from being very widely exploited.

USASRDL, in conjunction with researchers at Scientific Atlanta Inc., succeeded in developing a process whereby the variation in dielectric constant could be achieved by forming the sphere of concentric shells, the refractive index of each varying from the preceding in the proper manner. This development allowed a rapid, economical and accurate way of fabricating the Luneberg lens. This is believed to be the

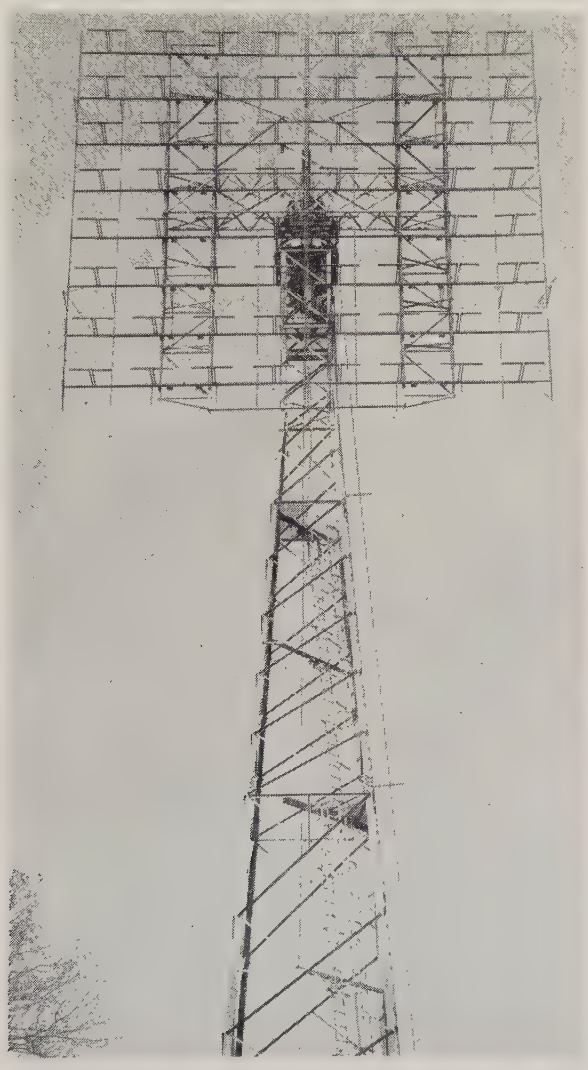

Fig. 1—First antenna to contact moon.

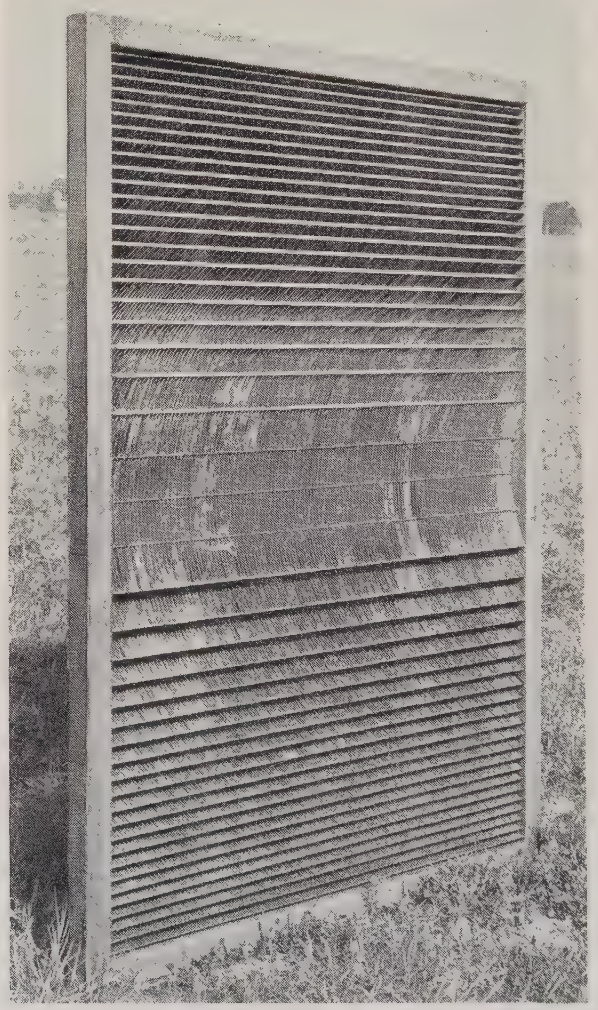

Fig. 2—Cylindrical waveguide lens antenna.

first practical three-dimensional Luneberg lens ever made to be usable at the relatively high microwave frequencies, and is shown in Fig. 3. Following this major breakthrough in the art, numerous applications involving the spherical Luneberg lens both as an antenna and as a static reflector resulted.

A two-dimensional Luneberg lens had been developed by researchers consisting of a circular section of parallel plate waveguide deformed in such a manner that the ray traveling diametrically across the circle had a longer path length than rays emanating from a point on the circle at an angle to the diameter. This difference in path length is exactly analogous to the difference in refractive index which would be observed if a slice were taken at the equator of a spherical Luneberg lens. The entire structure somewhat resembled the World War I military helmet and is sometimes called a "tin hat" antenna.

Although an interesting embodiment, this type of antenna did not find much application until the scientists at USASRDL decided to make use of the circular symmetry involved by employing a "tin hat" as a wide angle scanning antenna. By properly deforming a section of the circumference of the antenna so as to form a lip and developing a turnstile switch mechanism, the Georgia Institute of Technology under contract to the Signal Corps, built a geodesic analog of the Luneberg lens which could scan a one-degree beam over forty-five degrees at the rate of twenty scans per second with essentially no beam deterioration. This antenna was incorporated into an experimental mortar locating radar and showed very good results. Fig. 4 shows a double lens structure mounted in place for a two-beam application. This type of scanning antenna has also been successfully applied to a variety of other systems, including a millimeter surveillance radar and a millimeter airborne radiometer.

As the trend towards the still higher frequencies continued, it was realized that radically different techniques and components would be required if the millimeter region were to be opened for exploitation. The Signal Corps pioneered in making available the 70,000-Mc region by having necessary components developed, such as magnetrons, klystrons, waveguide components, detectors, and of course, antennas.

One of the promising scanning antennas which had been developed during the war was the Foster scanner, which involves a split cone rotating inside a conical stator. Attached to both the stator and rotor are toothed barriers which intermesh on rotation of the rotor. Proper mechanical tolerances were difficult enough to achieve at the lower microwave frequencies; at millimeter frequencies these tolerances became prohibitive. By developing a technique which eliminated the barriers the way was opened for using the Foster scanner at millimeter frequencies and improving its utility at the lower frequencies. The elimination of the barriers was accomplished by substituting for them a choke slot of proper design in the rotor. This development was carried through by the Stanford Research Institute under Signal Corps sponsorship. Making use of this choke slot principle, the ITE Company developed a choke slot millimeter Foster scanner to be used with a USASRDL-built radar set. This antenna scanned a 0.2° beam through 30°, at a rate of up to 40 scans per second. At close range, a beam of this type, when coupled with scan in the perpendicular plane, should provide enough resolution to permit identification of objects by the

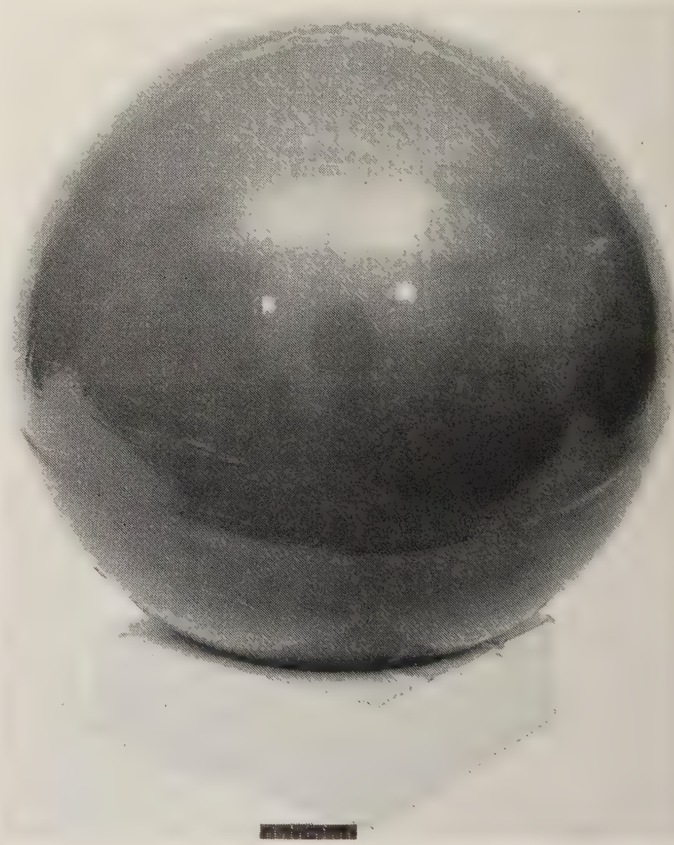

Fig. 3—Three-dimensional Luneberg lens antenna.

Fig. 4—Dual beam geodesic Luneberg lens antenna.

silhouette appearing on the display tube. This scanner built under Signal Corps contract was the first millimeter scanner in existence, and is shown in Fig. 5.

Another field in which the Signal Corps has been fairly active is that of broadband antennas. The typical broadband antennas used in the post-war period were either helices or spiral antennas. Much work had been done on these types but the effort, particularly on the latter type, was largely of an empirical and heuristic nature. The helix antenna although relatively broadband compared to existing types was still limited to approximately a two-to-one bandwidth. The spiral antenna although inherently much more broadband suffered from polarization and pattern deficiencies over a large part of the band. With Signal Corps sponsorship, engineers at the American Electronics Laboratory, Inc., combined the better features of both types in a conical helix which is essentially the projection of a single spiral on a cone. This structure yielded bandwidths in the order of ten-to-one with quite good circular polarization and pattern properties. The use of antennas of this type has minimized the number and variety of antennas required for field countermeasures installations. When it is realized that, just a short time ago, "broadband" implied bandwidth of 10 per cent to at most 100 per cent, it can be seen that current developments point out the great progress in the art.

To bring some coherency into the spiral antenna theory, Professor V. Rumsey of the University of California in cooperation with USASRDL engaged in a study of the theoretical aspects of the spiral. As a result of this work, a solution has been formulated for the currents and phase centers on spiral antennas required in order to satisfy the conditions for frequency independent operation. This is believed to be a major breakthrough in the theory of frequency independent antennas.

Another interesting project sponsored by the Signal Corps is that of a broadband direction finder, developed by Stanford Research Institute, which makes use of the multimode properties of a special type of ridged waveguide. This direction finder, simple and compact in structure, operates over a three-to-one frequency band with an rms error of about 2°. Variations of this system should find wide application in direction finding and electronic intelligence circles.

In the search for improved mechanical structures relating to the antenna field, the Signal Corps has done some pioneering work in air supported structures. One example is a series of dipoles operating in the HF range. Everyone in the communication field is aware of the difficulties of mounting and supporting the relatively large structures commonly used at these frequencies. The use of an air-supported dipole, sausage-shaped when inflated, provides an antenna at these frequencies which is easily stored, quite mobile, and easily erectable. The dipole itself consists of a plastic bag with a metal coating.

Following some early work at the Air Force in connection with large inflatable radomes which are essentially covers for antennas, the Signal Corps has done much work in investigating materials suitable for use with microwave radomes. These investigations culminated in air-supported radomes for the general SCR-584 type of antenna and the AN/CPS-9 radar storm detector. These radomes represent a considerable advance over the formerly-used solid plastic domes from logistic, maintenance and performance aspects. Fig. 6 shows a typical air supported radome installation.

Fig. 5—Millimeter Foster scanner antenna.

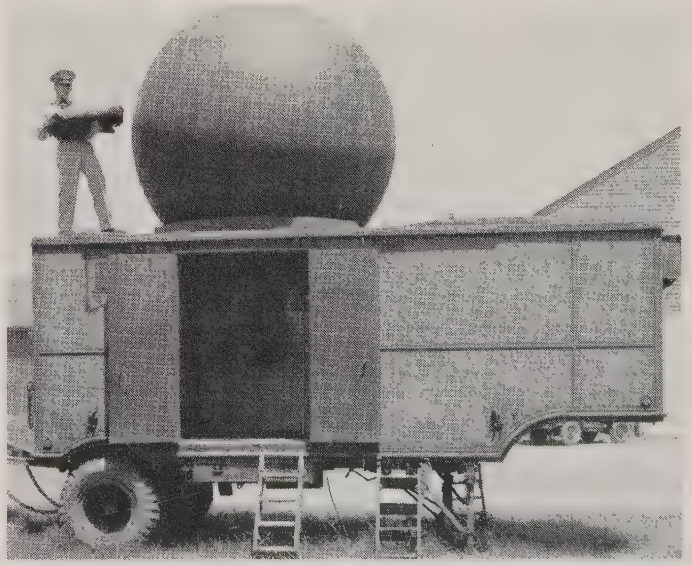

Fig. 6—Air-supported radome installation.

In the trend toward large antennas for use in connection with radio astronomy, space exploration, and satellite communication, the Signal Corps has contributed by research on the effect of variations of tolerances of these reflectors for the purpose of determining what the effective limits are on large antennas at various frequencies. This work has minimized the possibility of constructing large expensive antennas which would effectively provide no improved performance over somewhat smaller antennas. Also in the field of space exploration, Signal Corps engineers, using a specially designed antenna located at USASRDL, were successful in bouncing signals off the moon for the calibration of the world-wide net of Minitrack stations. The modern antennas used for space research are shown in Fig. 7 and may be contrasted with that of Fig. 1.

Fig. 7—Modern space research antennas.

Considerable activity is also being maintained in the application of new techniques to the antenna art. These include the incorporation of amplifying and transmitting components directly into the antenna structure for a variety of purposes. Many of these techniques are obviously still in the classified stage and for the time being will appear only in strictly military applications.

This summary of the Signal Corps antenna activities has been confined largely to the field of microwave antennas mainly because the author's experiences have been most closely associated with this field, and, at that, only developments which found reasonably wide application have been mentioned. Much progress also has been made in the field of communication antennas, particularly that of vehicular communication, where the contribution of the carrying vehicle has been taken into account so as to improve over-all performance. This subject is extensive enough to deserve separate treatment.

It is quite difficult to predict future trends in antenna research and application; but whatever the shape of the antenna of the future, it is certain that the Signal Corps will play a prominent role in moulding that shape.

Considerations of a Tropospheric Scatter System for Field Use*

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Summary—The modern Army will place greater demands on communication requirements for capacity, range and mobility. To meet these demands with conventional equipment results in a serious increase of manpower. The encouraging possibility of employing tropospheric scatter equipment to augment and possibly replace some conventional equipments has distinct advantages. This paper surveys the basic requirements of a tropospheric scatter system and expands them to fulfill the requirements of tactical employment. Subjects such as range and frequency dependence, effect of horizon angle, modulation techniques, and antenna gain degradation are reviewed to develop the technical foundation of a tactical system. The additional requirements of mobility, simplicity, and quick response are added to present a system designed for tactical utilization. Actual results obtained over a number of paths with digital data and facsimile transmissions are presented. The paper concludes with a discussion of inherent problems in tropospheric systems and the developments required to alleviate some of the difficulties.

* Received by the PGMIL, July 11, 1960.
† Army Electronic Proving Ground, Fort Huachuca, Ariz.

Introduction

THE possibility of employing tropospheric scatter systems within tactical units of the U. S. Army is becoming increasingly attractive due to their capability of providing reliable multichannel communications to ranges which heretofore required repeaters. Although radio relay, augmented with repeaters, is capable of providing the increased communications being required by combat elements, they are extremely costly in manpower and frequency spectrum. In addition, the location of suitable repeater sites is very often an untenable tactical position, *i.e.*, a hilltop. Second, in order to provide coverage into the near shadow areas, many of these radio relay systems operate in the lower VHF regions. This latter feature has created interference problems which are virtually insurmountable.

Although tropospheric scatter systems are by no means a panacea for the problems of tactical communications, they do offer certain advantages. This article describes the technical and tactical requirements of tropospheric scatter systems and results which can be attained with these systems.

Factors Affecting Performance of Tropospheric Scatter Systems

The tropospheric scatter signal has a short-term characteristic which is a Rayleigh distribution superimposed on a long-term variation in median level which is essentially Gaussian. The signals also exhibit seasonal variations, at least in temperate zones. To the practical communicator the factors of most interest are the persistence of these signals and the extremely large path losses. Measured path losses for a system operating in the 1-kMc region are shown in Fig. 1. From this it can be seen that the basic requirement of a tropospheric system is a large amount of system gain, as not all the power required can be derived from the transmitter.

In addition to these path losses tropospheric systems have other factors which significantly affect their performance. These are primarily frequency, horizon angle effect, antenna gain degradation, and meteorological effects. The frequency dependence factor is at present very elusive. Most experimenters have assumed a factor of 9 db per octave, as all data available appear to indicate a moderate increase in path loss with increasing frequency. Table I indicates results obtained by USAEPG on frequencies of 500, 1000, and 2000 Mc. Although this data is too insufficient to be conclusive, it does indicate that the factor of 9 db per octave is pessimistic.

The effect of horizon angle has been previously reported.[1] This factor does not appear to be wavelength dependent; its major effect is its impact on the siting of mobile terminals. A consoling factor here is the fact that most paths which exhibit rather large horizon angles also introduce other modes of propagation.

The remaining system parameter which affects the system performance is the antenna gain. Tropospheric scatter signals do not provide plane wave illumination of the aperture. This results in a realized gain which is less than the free space gain. The amount of loss in gain is a function of aperture size and path length. Table II shows some results of antenna gain degradation measurements over a 350-mile path at 810 Mc.

Since tropospheric scatter promises to make large scale use of the UHF band, the meteorological effects become significant. Of foremost importance is the refractive index gradient of the atmosphere. For mobile military applications it is insufficient to predict performance under normal conditions without considering the range of departures from normal. The problem becomes very acute when short-time circuits are considered. For example, one should not put in a circuit whose reliability, based on yearly medians, is marginal, if the circuit is to be operated only during the month of December when the worst propagation conditions exist. On the other hand, it is entirely possible for tropospheric systems to provide sizable signals well beyond their normal range under super-refractive conditions.

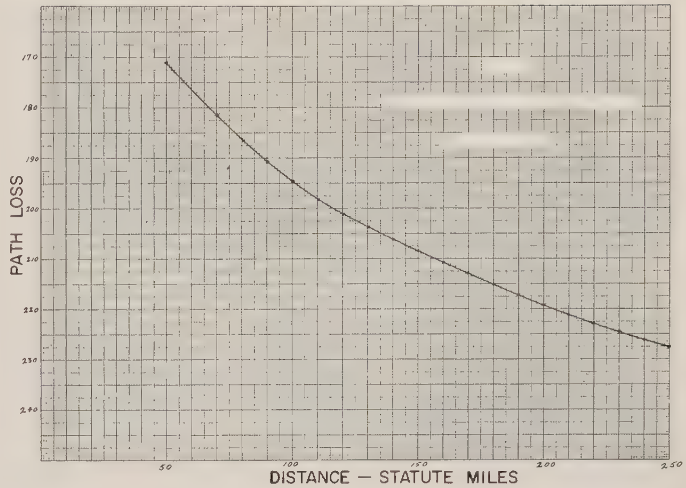

Fig. 1—Basic propagation loss 1000 Mc.

TABLE I

Frequency Dependence of Tropospheric Scatter. All Antennas Same Size—Equal Output Powers. All Measurements Simultaneous

Path Length	Rx Level 500 Mc	Rx Level 1 kMc	Rx Level 2 kMc
105		−88 dbm	−82 dbm
124	−94 dbm		−85 dbm
139	−97.25 dbm		−87 dbm
154	−97.25 dbm		−87.75 dbm

TABLE II

Antenna Gain Degradation Measurements on 350 Mile Path

Antenna Combinations	Difference in Median Received Level	Theoretical Gain Difference	Gain Degradation
A. 15 feet to 15 feet 15 feet to 28 feet	4.5 db	5.5 db	1.0 db
B. 15 feet to 28 feet 28 feet to 28 feet	4.0 db	5.5 db	1.5 db
C. 15 feet to 15 feet 28 feet to 28 feet	8.5 db	11 db	2.5 db
D. 15 feet to 28 feet 28 feet to 15 feet	0 db	0 db	0 db

Capabilities of Tropospheric Systems

A tropospheric scatter system is essentially a radio relay system with greater system gain than normal. As

[1] A. J. Svien and J. C. Domingue, "Tropospheric scatter propagation characteristics," 1959 IRE National Convention Record pt. 1, pp. 3–9.

such, these systems are capable of performing the same missions. In the case of tropospheric systems, however, the range of reliable performance can be extended well beyond that of radio-relay.

One of the basic misunderstandings of tropospheric systems was the doubt expressed as to their ability to handle high-speed digital data, or, for that matter, any information containing little redundancy. This doubt was created by the rapid fluctuations in level exhibited by tropospheric signals. With the addition of diversity and suitable combiners there appears to be no reason for this limitation. In actual tests at USAEPG over a two-hop circuit, the results of Fig. 2 were obtained when transmitting digital data at a rate of 2400 bits per second. From these results it can be seen that a fade margin of 17.5 db will provide an error rate of one error per 10^5 bits over a two-hop (110 miles each way) circuit. It must be pointed out here that the capability of handling high speed digital data is influenced more by the terminal (multiplex) equipment than by the radio systems. A very important parameter in the planning of data systems for application over scatter systems has been reported by Wright, *et al.*,[2] which considers the fade rate and the time duration of fades in tropospheric systems. From these results it appears that it may be necessary to establish a minimum bit length so as to avoid losing complete bits during deep fades.

In measurements on some 100 circuits over a three-year period at USAEPG, the reliability of tropospheric systems appears as shown in Fig. 3. The fade margin used as the ordinate is defined as the median signal level above FM threshold. Teletype copy, using standard Army page printers and telegraph terminals, was used for determining reliability. It is, of course, possible to transmit facsimile and voice over these systems, but the reliability is not quite uniquely defined for these cases.

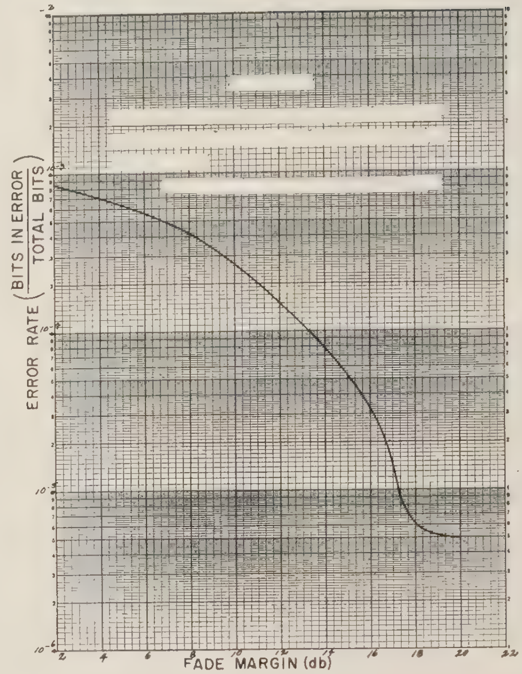

Fig. 2—Error rate vs fade margin for 110-mile 2-hop tropospheric circuit. Transmission rate = 2400 b/s.

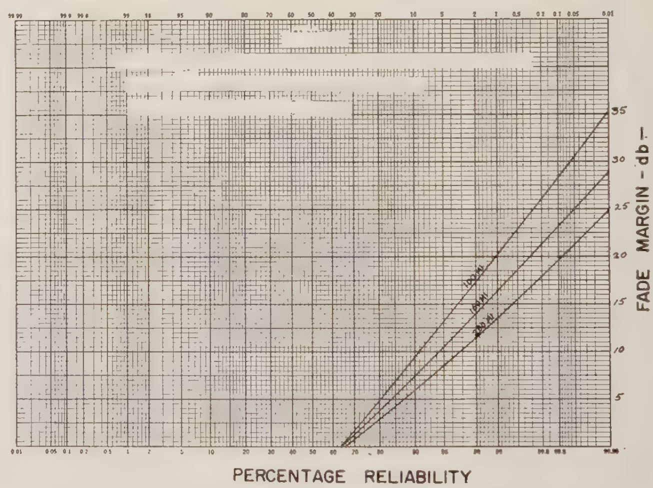

Fig. 3—Reliability as a function of fade margin for a dual diversity tropospheric system.

Other Advantages and Disadvantages

A factor not very often considered in the application of tropospheric systems is their inherent ability to utilize frequency bands which are much less crowded to provide, essentially, radio relay capabilities. As an example, our present-day radio relay equipment is purposely given a capability in the lower VHF ranges so as to permit operation in the near shadow regions. This practice, in addition to the nonmilitary assignments in this band, has created frequency assignment problems which are at best difficult to solve. Yet this very same capability could be provided by tropospheric systems in the SHF bands.

Another basic advantage of tropospheric scatter systems lies in their ability to eliminate the repeaters associated with normal radio relay when operating into the intermediate shadow regions. The use of repeaters in tactical operations requires extra equipment, operating personnel, logistic support, frequency assignments, and protection. All considered, the addition of a repeater to double the range of normal radio relay doubles the required personnel and frequency assignments, both very valuable commodities. A tropospheric terminal, on the other hand, can be operated with no additional personnel or frequencies.

It would indeed be remarkable if all the above advantages could be achieved without incurring some dis-

[2] K. F. Wright, *et al.*, "Measured Distribution of the Duration of Fades in Tropospheric Scatter Reception," presented at the 1959 Fall URSI Convention, San Diego, Calif.; October 19–21, 1959.

advantages. The basic problem with tropospheric systems has been their failure to support the basic concept of modern military operations, rapid reaction. With the path loss considerations previously covered and the fact that amplifiers with one kilowatt output are all that can be used in transportable systems, it is seen that the antenna becomes quite large. It is these large antennas and their required support structures which present the difficulties of tropospheric systems. Fig. 4 shows a tropospheric terminal designed to provide up to twelve channels of communications out to 150 miles in range. The system has 1-kw power output in the 1700–2400-Mc frequency range and utilizes two 15-foot air-inflated paraboloids in a space diversity arrangement. Although this system has shown that it is capable of providing the required communication, the minimum set-up time of two to three hours is intolerable. It is needless to say that by reducing the capability of this system it would be possible to reduce the antenna size and achieve a reduction in set-up time. However, when the always increasing demands being placed on communications capabilities are considered, the sacrifice of capability is a high price to pay.

Fig. 4.

Areas of Improvement

In considering the areas requiring improvement in tropospheric systems it appears that very significant contributions can be made in 1) the method of providing diversity, 2) the selection of optimum frequency ranges, 3) modulation techniques, and 4) receiver noise reduction.

By far the most common method of providing diversity in tropospheric systems is by means of space diversity, which requires a second antenna. This selection, which appears to have been made primarily in consideration of equipment economics, compounds the set-up time problem by requiring two very large antennas. A solution to this problem will probably be in the form of frequency diversity, but should not require the use of a second complete transmitter.

Selection of optimum frequency bands for assignment to tropospheric systems entails consideration of achievable receiver noise temperatures, antenna gain degradation, and path loss dependence. All considered, these factors point out that the lower UHF ranges are better suited to very long circuits, *i.e.*, beyond 400 miles. As the range is decreased, it becomes possible to employ higher frequencies more profitably.

Due to the large value of path loss experienced in scatter systems, it is desirable to use modulation techniques requiring minimum bandwidth for the transmittal of information. It is therefore to be expected that SSB has definite potential in improving the performance of tropospheric systems, particularly very long range systems. For mobile tactical systems the complexities associated with linearizing UHF power amplifiers and the relatively poor regulation characteristics of field power units will limit the use of this technique. Since FM does not suffer as much in these respects, it represents the majority of systems in existence, in spite of the fact that it is exhorbitant in use of bandwidth.

The advancements of the last few years in the reduction of receiver noise promise possibly the greatest single advancement in tropospheric systems. In addition to allowing reduction in antenna size, the development of these low noise devices also extends the frequency range available. The primary objection to these devices has been their tendency to be narrow-banded. The requirement for cryostats in the maser amplifier almost precludes its use in transportable systems. There is still considerable improvement to be achieved, however, through the use of the solid state parametric amplifier, provided the operation and tuning of this amplifier is not unduly complicated.

Conclusions

This paper has attempted to point out the consideration being given by the U. S. Army Signal Corps in applying the tropospheric scatter technique to the expanding field of communications for the Field Army. Some of the major problem areas have been identified with possible solutions pointed out. Although the paper attempts to point out the many advantages of tropospheric systems, it is well to add that any system which cannot be serviced and maintained by the average service technician is doomed to failure regardless of the magnitude of its advantages.

Acknowledgment

The author wishes to express his gratitude to a number of his colleagues at USAEPG, both military and civilian, as well as members of the Research and Development Division of Collins Radio Company for some enlightening comments and discussions on this subject.

Electromagnetic Environmental Testing*

R. E. FRESE†, SENIOR MEMBER, IRE, AND J. H. HOMSY†, SENIOR MEMBER, IRE

Summary—A number of factors which contributed to the establishment of the Army's Electromagnetic Environmental Test Facility (EETF) at the U. S. Army Electronic Proving Ground are reviewed. Technical planning to date covering the layout, organization and operation of the EETF is summarized. Finally, predictions as to the possible future scientific role and activity of the EETF are made.

IN addition to the exciting and fascinating technical problems presented by satellites and the exploration of space which have captured man's imagination and interest these days, military electronics is faced with another vitally important problem that is peculiar to our time and technology. It has come about because communications-electronics equipments are being utilized now in quantities not dreamed of just a few years ago. These equipments will experience serious and perhaps crippling mutual interference when they are used in their operational electromagnetic environment. Part of the Army's program to reduce mutual interference to a tolerable level is the creation and operation of an Electromagnetic Environmental Test Facility. In this facility equipment will be tested, under controlled conditions, in the electromagnetic environment in which it will be expected to perform in combat. For some years, the U. S. Army Signal Corps has recognized the need for such a facility. This need has culminated in obtaining the assistance of industry to establish the facility in relative isolation as a major effort of the U. S. Army Electronic Proving Ground at Fort Huachuca, Arizona.

This paper reviews briefly the background which has led to the creation of the facility, describes the technical planning to date, and predicts the role this facility will have in the future.

To be effective in battle, a combat commander must have reliable and effective communications for command control of his forces. He must have clear and thorough surveillance of the combat area and means of communication to channel the surveillance information to the places where it is used. He must have operational reliability of his missiles and his fuses which depend on electromagnetic waves for their guidance and activation, respectively. He must have effective operation of a myriad of devices and systems for direct and counter-operations including those for electronic warfare. These cover the entire gamut from a simple "handie-talkie" to complete navigation systems for his vehicles and local air defense systems.

The advent of the nuclear age and consequent highly mobile combat arms has placed extreme emphasis on electromagnetic means to accomplish the functions a combat commander requires. This emphasis has caused the number of radio and radar emitters in a combat area to grow manifold in the few short years since World War II. Fig. 1 shows that a Field Army, at the end of World War II, contained approximately 23,000 electromagnetic emission devices. If we should go to war today, a Field Army will have about 75,000 such devices in an area approximately 100 miles on a side. The devices of nearby Army units, the Air Force and the Navy, our Allies and the enemy also will contribute to the electromagnetic environment in which a Field Army operates.

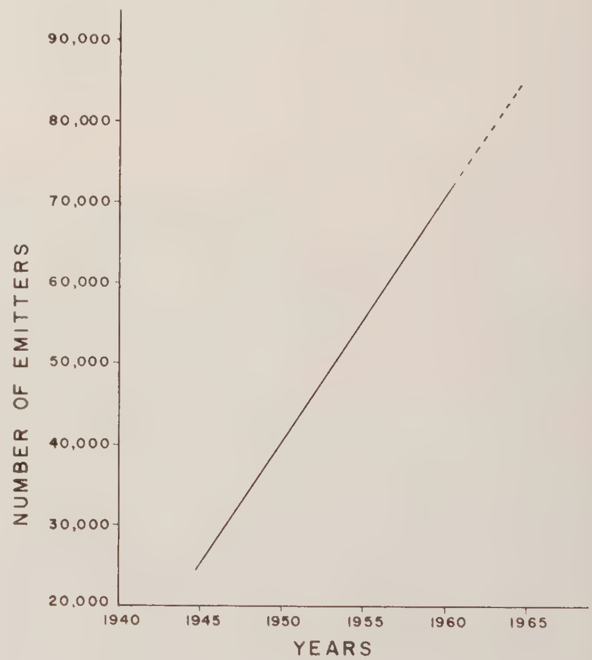

Fig. 1—Growth of emitters in a field army.

New and additional equipments are under development now so that future increases in the quantity of devices can be expected. In addition to quantity, developers have called upon higher and higher power emission in order to obtain greater operating range of their devices, to thwart potential countermeasures threats, or to avoid interference from other devices. Some radars today emit greater power through antenna sidelobes than was emitted through the main lobes of comparable radars during World War II. This increase in power level, coupled with increases in receiver sensitivity, has compounded the interference problem. An indication of the potential of the interference problem was given in the Korean conflict. There, interference effects were noted and investigated by the Baker Mission. The man-

* Received by the PGMIL, July 11, 1960.
† U. S. Army Electronic Proving Ground, Fort Huachuca, Ariz.

made electromagnetic environment in which communications-electronic equipment is expected to perform is an important fact-of-life which can no longer be ignored.

The military services have conducted more than eighty studies to alleviate interference, to improve frequency assignment techniques, and to determine the impact of electromagnetic incompatibility. These include the comprehensive studies of the Army's Project Monmouth and those on radar and IFF by the RAND Corporation for the Air Force. These studies have formed the basis for the planning and implementation of the Electromagnetic Environmental Test Facility. This facility, by proper balance of field experimentation, analysis, and mathematical modeling will reveal existing incompatibilities of equipments and systems, will suggest modifications to present equipment to reduce interference, will provide a firm basis for the establishment of realistic standards for new equipments, will enable the controlled testing of frequency assignment plans and concepts, and will permit the proof testing of new equipment prior to standardization.

The plan for the Electromagnetic Environmental Test Facility is a practical compromise between two impractical extremes, all field or maneuver testing and all mathematical modeling. The facility will consist of three integrated parts: an analogous duplication of the electromagnetic environment, measurement and monitoring facilities, and a mathematical model, all interrelated as shown in Fig. 2.

The initial two-year program provides for the analogous duplication of the electromagnetic environment generated by a tactically deployed Army Corps, in which Division equipment will be tested. The environment will be created systematically, progressing from smaller to larger units, so that useful information will be obtained throughout the two-year period. Although the Electromagnetic Environmental Test Facility program initially considers the incomplete environment generated by the smaller Army units, it is the intent to diagnose the incompatibility ills that exist in these units before attempting the more challenging task of investigating the larger complex of equipments.

Actual troops and actual transmitting equipment will be used to create the environment for squad, platoon and company level testing. The company level testing capability will be accomplished by October, 1960. As battalion, battle group and division capability is established, transmitting portions of Army hardware will be deployed singly or in groups within and near the measurement areas for the creation of the environment, as shown schematically in Fig. 3. At greater distances from the measurement areas, simulators will be used to complete the environment at least expense. Simulators will be used only when the devices they represent do not emit spurious signals that would reach the measurement areas. Tactical realism of the generated environment is a necessity. Therefore, emitters, other than simulators, will be adjusted and tuned by military personnel who are normally responsible for such tasks in the Army because faulty or improper operation, as well as faulty or improper design, contributes to interference. The effects of unintentional radiators such as spark plugs and electric motors will be considered also.

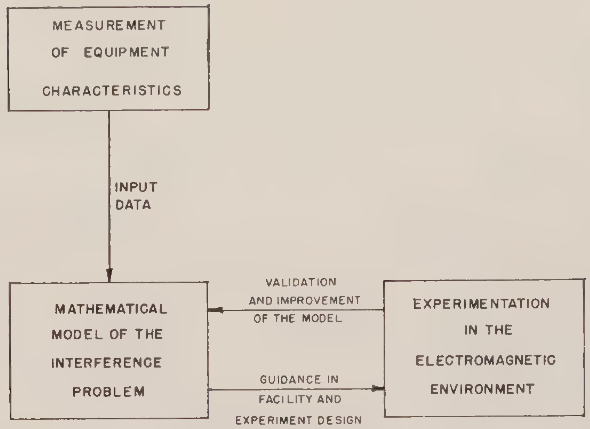

Fig. 2—Interrelation of the three parts of the Electromagnetic Environmental Test Facility.

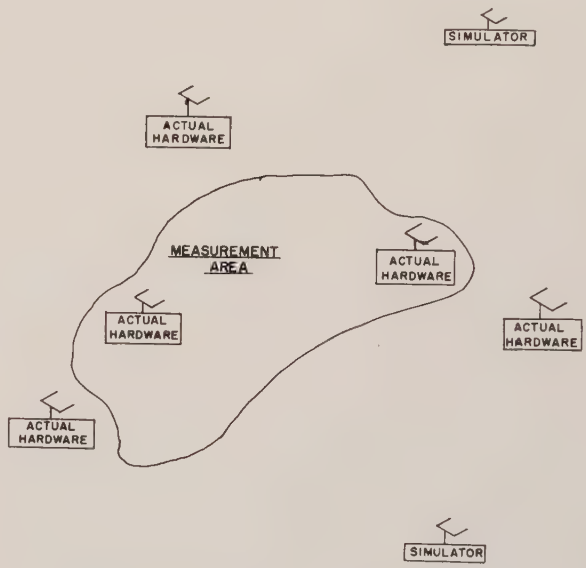

Fig. 3—Deployment of equipment to create the environment.

Beginning with the environment generated for the testing of battalion equipment, the emitters will be controlled by cards so that preplanned experiments can be conducted efficiently and economically. It must be noted that in order to duplicate the electromagnetic environment generated by an Army Corps at a particular time, only that fraction of its 13,000 emitters which emit simultaneously at that time need be represented in the deployment of equipment and simulators in and near the test areas. The deployment of small amounts of additional equipment will allow rapid changes among possible environments without physically transporting equipment. In this way, the facility for generating the electromagnetic environment will provide, economically, a high degree of flexibility in the environment.

The monitoring and measuring facilities will provide the means by which: 1) interference among tactically deployed standard equipment will be noted and investigated; 2) new equipments and frequency allocation plans will be tested; 3) data for the construction of a mathematical model will be obtained; 4) the mathematical model will be validated; and 5) other users of the electromagnetic spectrum in the vicinity will be protected.

The monitoring and measuring equipment includes tactical receiving equipment and receiving portions of tactical equipment deployed realistically throughout the measurement areas. Data will be acquired in a form such that they can be processed by the IBM 709 computer at Fort Huachuca according to analysis procedures planned simultaneously with the design of the experiment. Obvious incompatibilities may be noted in the field. Subtle incompatibilities will require sequential type of experimentation and analysis.

Although it is generally agreed that less interference is better than more interference, the impact of interference on tactical operations must be determined in order to provide the framework within which the cost of modification to and replacement of standardized equipment can be viewed. Therefore, the experimental data and computer analysis of them will be designed to be compatible with and complementary to the Combat Simulation Model Project which is under development by the Signal Corps at Fort Huachuca. The use of this mathematical model will provide, among other things, the specific effects of interference and incompatibility on tactical operations and will provide a means by which modifications to the communications structure, suggested as a means to reduce or eliminate interference, will be examined to determine their effect on tactical efficiency.

Proof testing of new equipment and frequency assignment plans, the second provision of the monitoring and measuring facilities, is viewed from two aspects: first, the existent environment must not interfere with the proper operation of receiving portion of the new equipment; and second, the new environment, containing the contribution of the emitting portion of the new equipment, must not interfere with the operation of the existing receivers. Note that in addition to testing new equipment in a realistic electromagnetic environment, the deployment of standardized receiving equipment throughout the measurement areas provides simultaneous testing of many possible incompatibilities. This capability for simultaneous testing also permits frequency assignment plans for tactical forces to be tested quickly and realistically.

It has been recognized for some time that the available data on both the desired and spurious emission characteristics of our electromagnetic radiating devices, on the response characteristics of our receivers, and on the nonlinear combination of signals within the receivers, are not adequate for the formulation of a mathematical model of the electromagnetic interference problem for tactical Army forces. Data on propagation phenomena and detailed antenna patterns of tactical equipment are also inadequate. The third provision of the monitoring and measuring facility is the collection of these data within the measurement areas, on an antenna range and in a laboratory facility. Unusual emissions or responses may initiate immediate recommendations for equipment modification.

The fourth provision of the monitoring and measuring facility is to supply the means by which the mathematical model of the electromagnetic interference problem can be validated. Even while the environment created in the measurement areas duplicates only that of small Army units, identical experiments will be performed in the field and on small versions of the model. Differences in the outcome, if they are statistically significant, will be investigated and their causes will be used to improve and refine the smaller versions, leading to eventual validation of the full scale model.

Protection is the fifth provision of the monitoring and measuring facility. In spite of the relative electromagnetic "quiet" of the desolate areas of Arizona in which electromagnetic environment will be created, commercial and private users of the electromagnetic spectrum must be protected. Complete monitoring facilities will be maintained to prevent such interference and will also be maintained to prevent extraneous commercial or private emissions from distorting the duplicated environment.

Closely integrated with duplication of the environment and the monitoring and measuring facilities is the mathematical model of the electromagnetic interference problem to be programmed for the IBM 709 computer at Fort Huachuca. Because of the nature of the problem, the model will be stochastic. Its formulation will be based on the many studies that have been conducted, techniques developed by others for this type of modeling and experimental data obtained from the monitoring and measuring facilities. The model will be used to assist in the programming and operation of the measurement area and in the design of experiments to be conducted in the field. It will also be used in studies of the optimum number of electromagnetic radiators to be used to represent statistically the typical environmental contribution of each equipment type, thereby contributing to economy of operation. Once the mathematical model is properly validated, it will be used to extend the experimentally confirmed knowledge to other types of terrain, climate, and deployment that cannot be realized in the vicinity of Fort Huachuca.

The Electromagnetic Environmental Test Facility is a practical compromise between two impractical extremes. An attempt to solve the interference problems by experimentation alone would be too expensive and unwieldy. Field maneuvers that are conducted periodically for other purposes offer no opportunity for controlled quantitative investigation. It is not feasible to solve the problems solely by the use of mathematical models

because there are not at hand today sufficient data for formulating the model. In any event, the validity of such a model requires confirmation in the type of controlled environment which this program will provide.

The Electromagnetic Environmental Test Facility with its duplicated environment and monitoring and measuring facilities can be viewed as a carefully instrumented, digitally controlled, large, outdoor, analog simulator wherein many real components are used; with a mathematical model to guide the operation and extend the result. Operation of this facility will reveal the incompatibilities of tactical equipment and systems and generate specific recommendations for modification of equipment and suggest changes in frequency assignment systems to reduce interference. With the work of others it will provide the basis for the establishment of realistic standards and specifications for future production of equipment which will limit spurious emissions and unwanted responses to a tolerable level. It will provide a "wind tunnel" in which frequency assignment plans and concepts can be tested and a facility in which the compatibility of new equipment with that already standardized can be examined. When in operation, the duplicated environment will be a valuable training ground for Signal and other units for coping with a realistic, tactical electromagnetic background.

Picture now the Electromagnetic Environmental Test Facility, as part of the Army's over-all program for interference control, as it will be at the conclusion of the two-year program. It will be kept within logistical bounds through the use of simulation and modeling. Automation will be used effectively for control of the environment and for measurement. Included will be sufficient manual operation to assure that human factors are not overlooked. The form in which the facility will be expanded to include larger units, sister services and the enemy will depend upon the accomplishment of the first two years.

Signal Corps Field Telephones*

RAOUL A. FARALLA†, SENIOR MEMBER, IRE

Summary—**Signal Corps pioneering in the design and development of U. S. Army field telephones is discussed. Explanation is given of the military need for the new features and performance improvements desired in field telephones, and of the methods whereby these new requirements were resolved by Signal Corps engineers. In each instance, the Signal-Corps-developed field-telephone sets performed better than contemporary commercial telephone sets. A few of the Signal Corps inventions and innovations have been adopted by the U. S. telephone industry and incorporated into the design of the latest subscribers' telephone sets, whose improved performance is now comparable to that of present standard Signal-Corps-developed field-telephone sets.**

The new features of the recently developed, fully transistorized, Signal Corps field-telephone set for use with the completely automatic, electronic-switching, military-communication system are also discussed. The novel circuit features of this telephone make it possible, for the first time, to have a subscriber's line carry only voice-frequency currents at voice-frequency communications level.

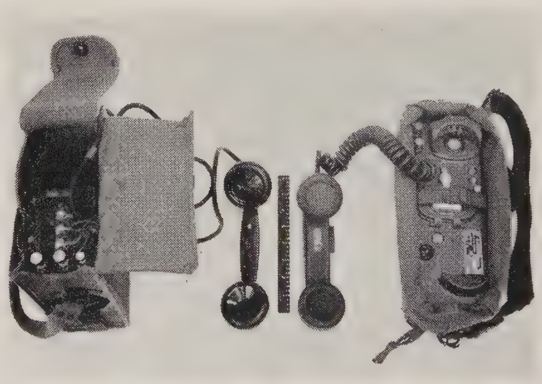

Fig. 1—Telephone EE-8 and Telephone Set TA-43/PT (standard). Group view showing both telephones in operating condition.

I. Telephone EE-8 (Fig. 1)

THE YEAR 1936 marked the start of a new era in the performance of U. S. Army field telephones, for that was the year that Telephone EE-8 (Fig. 1) was born. This telephone was a pioneer, as its performance was an improvement over existing commercial telephones. Information on which to base the performance requirements for this telephone was furnished by the Bell Telephone Laboratories. The "nonpositional" carbon transmitter element made it possible to hold the telephone handset in any position from full face-down to full face-up and still be able to maintain communication with the distant party, with some degradation in output. The specified microphone frequency response was 600 to 3000 cps.

To compensate for the greater attenuation of the higher audio frequencies by the field wire, the microphone was designed to produce a rising characteristic of approximately 1 db per octave. The handset receiver response was similar to that of the handset microphone.

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.

This telephone gave satisfactory communication over a 30-db-loss field-wire circuit.

Telephone EE-8 was designed by U. S. Army Signal Corps engineers[1] at Fort Monmouth, N. J., and service-test models, based on the Signal-Corps-built development model, were procured from the Automatic Electric Company in 1937. The service test of Telephone EE-8 was made late in 1937, and the telephone, with minor modifications, was standardized for production in 1938. To avoid possible bottlenecks in the production of the EE-8 in case of war, production contracts were purposely given to each of the relatively large independent telephone companies,[2] and the Western Electric Company. Telephone EE-8 has an excellent World War II record for performance and reliability under actual combat conditions, and is conceded to be the best field telephone used by any army during World War II.

II. Telephone Sets TA-43/PT and TA-312/PT (Fig. 2)

World War II experience showed that Telephone EE-8 had quite a few shortcomings, namely: inability of the carbon microphone diaphragm to withstand bomb-blast or relatively close mortar-fire explosions; inability to hear the telephone bell under relatively high battle-noise conditions; inability to control the bell output from a minimum (whisper level) to maximum; inability of the instrument to withstand complete immersion in amphibious operations; and inability to operate the handset switch with arctic gloves. Other desirable improvements were: a 6-db increase in talking range; a broader frequency response of 300 to 3500 cps as an aid to voice recognition and intelligibility; a longer battery life; addition of a full common-battery operation feature; ability to remotely control a radio transmitter in push-to-talk operation; a "noncogging, free-spin" generator; thinning the receiver end of handset to fit under helmet; improved emergency "sound-powered" operation; and reduction in weight as much as possible.

Solution was effected as follows. The length of the handset was shortened by $1\frac{1}{2}$ inches giving approximately $1\frac{1}{2}$-db improvement on transmission. This shorter length was quickly applied in 1948 to the design and production of Handset H-33/U, the Army standard handset used with the "GRC" series of Signal Corps vehicular radio sets. This shortened handset has the same length as the Bell System "500" subscribers' telephone set (see Fig. 3).

The problem of overcoming the damaging effect of shell explosions on the handset microphone was solved by using 0.001-inch-thick Nilvar stock in the proper configuration to give the desired 300- to 3500-cps frequency response. An improvement in diaphragm sensitivity of 0.5 db was also obtained as compared to that of the aluminum diaphragm used in the EE-8 handset.

Improved output from the carbon microphone was obtainable only by improving the carbon granules. By a combination of: mechanical agitation, subsequent sifting, removal of the fine powder clinging to the granules, and exposure to controlled atmosphere, carbon granules were obtained which physically and chemically change very little in use. The efficient utilization of space by these granules in the carbon button and the lack of "frying" noise resulted in a 3- to 4-db increase in transmitting range. This process of artificially aging the carbon granules has been adopted by all U. S. telephone companies for use in all the latest "500"-type subscribers' sets.

The "bell" problem was solved by the Bell Telephone Laboratories by using a balanced-armature type structure, the end of the armature having a striker, the striker to hit a metallic cup, the cup to act as a resonator for the selected frequency, and the intensity of the blow on the cup controlled by restriction of the travel of the striker before it hits the cup. Inasmuch as WW-II studies on hearing loss of combat personnel disclosed that the ear suffers a loss in sensitivity and that this loss is least at approximately 2400 cps, a resonator cup frequency of 2400 cps was chosen. The harmonics of the 2400-cps resonator cup gave a peculiar woodpecker sound, which under battle-noise conditions was audible at twice the distance of the standard telephone-type bell with the same amount of power. A manually-operated cam controlled the striker travel so as to regulate the wood-

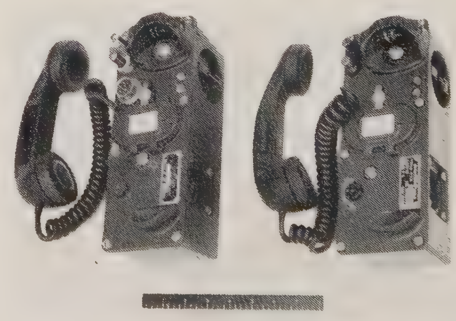

Fig. 2—Telephone Set TA-43/PT and Telephone Set TA-312/PT (standard). Group view of complete units, showing telephones in operating condition, carrying cases removed.

Fig. 3—Comparison of handset sizes (standard). Group view showing (left to right) handset of commercial "302"-type telephone; handset TS-9 of Telephone EE-8; handset H-33/U of GRC series radio sets; handset H-60/U of Telephone Set TA-43/PT; and handset of commercial "500"-type telephones.

[1] G. O. Tapper and R. A. Faralla.

[2] Automatic Electric Co.; Stromberg-Carlson Co.; Kellogg Switchboard and Supply Co.; Leich Electric Co.; North Electric Co.; Holtzer-Cabot Co.; Connecticut Telephone and Electric Co.

pecker sound output from the equivalent of a whisper to its maximum loudness. This item is nomenclated Buzzer BZ-23/PT (see Fig. 4).

The needed 3-db increase in receiver efficiency was obtained by using a "UI"-type Western Electric Company handset-receiver unit modified to permit the thinning of the receiver end of the handset so that it could be inserted under the Helmet M1.

Increased battery life was achieved by the design of a resistance-controlled current-limiting carbon-microphone circuit, which limited the current to approximately 90 ma with two fresh flashlight batteries; a current of 60 ma was still obtained when the batteries reached their useful end voltage of 1.1 volts per cell. This relatively simple current limiting curcuit increased the life of the batteries by approximately 500 per cent.

Common-battery operation was achieved by a second induction coil and by the design of a companion silicon-carbide varistor current-limiting circuit as used in the Bell System 500 Set. The value of the microphone current was limited to approximately 60 ma, irrespective of the length of the line.

Radio remote control was achieved by the addition of a second set of make contacts to the push-to-talk switch in the handset handle. With the selector switch in the LB position, operation of the push-to-talk handset switch automatically placed a retardation coil across the line, thereby closing a dc current path to operate the *transmit-receive* relay in the remote radio. The inductance of the bridged retardation coil was sufficiently high to limit the shunting effect on voice-frequency currents.

A noncogging, free-spinning, hand-driven 20-cycle ringing Generator G-42/PT (Fig. 4) was developed by the Holzer-Cabot Company in connection with a previous field switchboard development.

Operation of the handset switch with arctic gloves was accomplished by locating this switch on the side of the handset handle and using the thumb to operate the switch.

Antifrosting protection for the microphone was accomplished by means of a detachable voice-frequency transparent polystyrene membrane that is snapped into place on the handset microphone cap.

Improved battery-less operation was effected by the combination of greater handset-receiver sensitivity and better impedance matching between the handset-receiver circuit and the field-wire line. This arrangement permitted communication over a 3-mile length of field wire as compared to the previous $1\frac{1}{2}$ miles.

Immersion-proofing was accomplished by providing water-tight seals wherever needed.

A telephone weight reduction of 2 pounds was achieved by the use of aluminum for the telephone case, and by reduction of the weight of all telephone components to a minimum, consistent with required reliability and reasonable cost.

The Bell Telephone Laboratories, Inc. developed the components and constructed the development models. This field telephone is known as Telephone Set TA-43/PT, and approximately 120,000 of these have been procured. A slight modification has been made to permit connection of a headset-handset for hands-free operation when the telephone is used in map-plotting operations or as an auxiliary operator's telephone circuit. This modified set, of which approximately 110,000 have been procured to date, is the present standard U. S. Army field telephone set known as Telephone Set TA-312/PT.

Telephone Set TA-1/PT (Fig. 5)

Battery-less (sound-powered) telephones play an important part in front-line short-range communications. Their light weight makes them extremely desirable. During WW II, sound-powered Telephone TP-3, which weighed 6 pounds and had the dimensions of Telephone EE-8 was used for point-to-point operation and could be connected to other Telephones TP-3 or EE-8 either directly or through magneto field switchboards. Besides the excessive 6-pound weight and relatively large size, Telephone TP-3 was deficient in many ways. Its 3-mile transmission range over field wire was too short, as a 5-mile range was needed. A control was needed to regulate the sound output from the ringer. In the ringer *off* position, a visual indicator was needed to indicate the existence of an incoming call, the indicator to remain *on* until the call was answered. The telephone

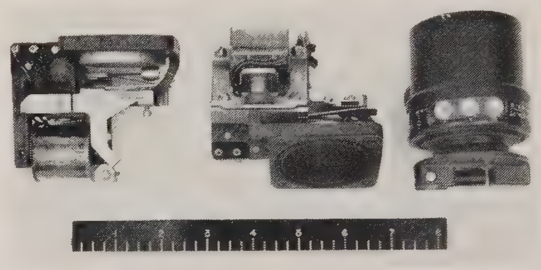

Fig. 4—Buzzer BZ-23/PT and Generator G-42/PT (standard). Part of Telephone Sets TA-43/PT and TA-312/PT. Group view showing clapper ball and resonator cup on buzzer.

Fig. 5—Telephone TP-3 and Telephone Set TA-1/PT (standard). Group view of complete units, showing telephones in operating condition.

had to be immersion-proof. Provision had to be made to prevent frosting of the microphone in freezing temperatures, and to prevent mud and dirt from entering the microphone and receiver caps. A free-spinning 20-cycle generator was needed, capable of ringing magneto switchboard over 5 miles of field wire; the generator to be actuated by the squeezing action of the hand. The push-to-talk switch and the 20-cycle generator-actuating lever had to be operable with arctic gloves. The receiver end of the handset telephone had to be thin enough (1 inch) to fit under combat Helmet M1. By using the latest type of permanent magnet material in the proper configuration, and a complete redesign of the balanced armature type structure, the size and weight of the sound-powered microphone and receiver units of the TP-3 were reduced by one half and the performance was about 1 db better. Redesign of these sound-powered units was accomplished by RCA under Signal Corps development contract.

The ringer or buzzer problem was solved by a redesign of the original woodpecker sounding buzzer of Telephone Set TA-43/PT, and the manually-controlled *volume-limiting* and *volume shut-off* indicator lever was incorporated in the face of the buzzer (see Fig. 5).

The big stumbling block was the design of the "squeeze" 20-cycle generator, which, in addition to the free-wheeling-drive feature, had to be small enough to fit in the handset-type telephone handle. The Holzer-Cabot Company, pioneers in the design of efficient small generators and motors, was awarded a development contract for Telephone Set TA-1/PT, since the microphone and receiver units that RCA developed for the Signal Corps were to be furnished to the contractor. After considerable design effort, a lever-actuated, free-wheeling 20-cycle generator was designed, fabricated, tested, and met all the specified military requirements.

The design of the desired visual indicator was patterned after the WW II German Maltese-Cross switchboard signal. The maltese cross was made luminescent so as to be barely visible at night, and it was mechanically coupled to the telephone *push-to-talk* switch. This arrangement allowed the visual signal to retract or disappear the first time that the *push-to-talk* switch was operated in answering a call.

Immersion-proofing was effected by the use of gaskets and neoprene boots wherever needed. The watertight microphone acoustic membrane was also antifrosting.

With the exception of the microphone and receiver units, all components are mounted on a single chassis that can easily be separated from the handle by removing four screws at the microphone end of the handle. This arrangement is ideal for servicing. The location and size of the generator-actuating bar and push-to-talk switch are such as to permit operation with arctic gloves.

The telephone case or handle was made of aluminum, properly treated and painted to withstand military field usage. The weight of this handset-shaped telephone is 2.2 pounds, including its 6-foot retractile connecting cord and plug, and its length is the same as that of the handset of the TA-43/PT. This is considered quite an advancement in the state of the art.

Service-test models of Telephone Set TA-1/PT passed service test and was approved for standardization in two months; a record for such action.

Telephone Set TA-341 ( ) /PT (Fig. 6)

With the anticipated changes in the type of warfare, atomic-nonatomic, mobility of field troops is tantamount to survival. Therefore, the location of a given combat division is continually changing and it is practically impossible to maintain an up-to-date directory for the proper routing of calls during combat operations. An automatic switching system, capable of automatically routing a call to a given coded unit, irrespective of location, appears to provide the needed flexibility. A dial-type telephone does not lend itself to military field use because of the vulnerability of the dial to dirt, mud, ice, etc. A push-button type of pulsing mechanism, which can be totally enclosed, is the answer.

A subscriber's line, connecting a dial-type telephone to an automatic-switching commercial central office is, in the communications sense, a very contradictory transmission line, when one considers that its primary function is to carry two-way voice-frequency currents of very low power, usually below 1 mw. By present-day standards, however, this very same line is also made to carry dc currents of 60 to 340 ma, solely for the purpose of furnishing power to the carbon microphone in the subscriber's handset. The value of this dc current is dependent on the distance or loop length of the subscriber's set to the central office, and the dc power expenditure ranges from 3 to 17 watts. In addition, this same subscriber's dc power line must also be a 20-cycle ac power line, as approximately 3 watts of 20-cycle power must be supplied from the central office for ringing the subscriber's set bell. In contrast, the ideal subscriber's line would be one that carried solely voice-

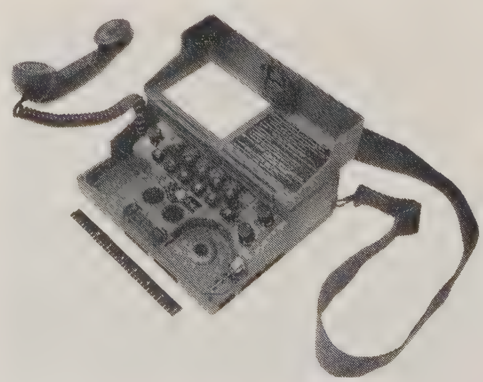

Fig. 6—Telephone Set TA-341 ( )/PT (development). Over-all view of complete unit showing telephone in operating condition, tone radiating horns in base and imbedded magnets of magnetic hookswitch.

frequency currents, of voice-frequency transmission levels not exceeding 1 mw.

Plant investment in existing commercial automatic switching telephone systems renders the adoption of this ideal subscriber's line uneconomical. A brand-new military automatic switching communication system does not have this tremendous financial handicap; therefore, the design of a new 4-wire subcriber's field telephone, predicated on effecting this ideal subscriber's 4-wire line, is not only feasible but highly desirable. Again, the Signal Corps set out to pioneer in field telephones by creating an entirely new design for 4-wire subscriber's sets. The advent of transistors capable of meeting military requirements, and their relatively very low operating current, made possible the full transistorization of the telephone set. By the requirement that all the needed dc power to operate all transistors be included in the telephone set proper, the need of a dc current supply from the central office was eliminated. In addition, the telephone could also be used for point-to-point unswitched operation. The inherent vagaries and noise of a carbon microphone are eliminated by the use of a generator-type microphone element in the set and the amplification of its output by a transistor amplifier capable of supplying a maximum line output level of 1 mw.

By designing the set so as not to require the receipt of 20-cycle ringing ac power, the need for ac current supply from the central office was eliminated. This elimination was accomplished by providing the field telephone set with a quiescent local transistor oscillator, which is triggered by an incoming low-level, voice-frequency signal from either the central office or from another field set. The output of this triggered local oscillator was then fed into the handset receiver creating the desired loud voice-frequency sound; the receiver performing the additional function of an equivalent bell. Inasmuch as this second "bell" function has to be performed while the handset rested in its cradle, a modified exponential horn molded into the set couples the handset receiver as it rests in the cradle, the mouth of the horn emerging through openings in the base (these openings are unaffected by the opening or closing of the telephone case).

The output of the local quiescent-ringing oscillator is centered at 2700 cps, which is the most desirable "bell" frequency under combat conditions. By manual control of the ringing oscillator output, the sound output of the receiver unit, when doubling as a bell, can be regulated from a mere whisper to maximum loudness. The ringing oscillator dc current drain during its quiescent state is 15 μa, and for maximum output, the dc current drain is 25 ma (equivalent to a power drain of approximately $\frac{1}{4}$ watt as contrasted to the 3 watts of 20-cycle power previously required from a central office or switchboard). The 15 μa constant drain on the field-telephone set dry batteries is not detrimental, as this drain makes the batteries' life practically equal to their shelf life.

Digit dialing is accomplished by means of compound audio-frequency tones, obtained by combining the output of two different frequency transistor oscillators. The pre-determined compounding is automatically effected by the mechanical motion of the push button being actuated. Two master oscillators, 1900 and 2700 cps, respectively, supply a total of 6 different frequencies by means of different resistive and capacitive components. Thus two adjacent frequencies are obtained, each of which is 200 cycles different from the master-oscillator frequency. The telephone is powered by 6 "C" size flashlight cells mounted in a special battery holder, and supplying 9 volts for the operation of the entire field-telephone set.

Another innovation is the magnetically operated hookswitch, which greatly simplifies the handset *on-cradle* and *off-cradle* operation of the hookswitch and holds the handset in place. Two ceramic permanent magnets are molded in the case, and the handset handle contains a molded-in piece of soft iron that bridges the two magnets when the handset is in the cradle, thereby completing the magnetic circuit, and causes the rotation of an iron armature in the set which controls the actuation of the hookswitch.

Circuit design includes provisions for: point-to-point wire, point-to-point radio, and switchboard-type operation. A connector is provided for attaching a headset-handset to the telephone in case hands-free operation is desired. A switch is also included to permit choice of: handset only, headset-handset only, or both.

Communication in the relatively high ambient-noise conditions is enhanced by incorporation of a receive amplifier whose output is manually controllable, to cope with the existing transmission and ambient-noise conditions.

With the exception of the handset, all components are housed in a waterproof fiberglass case. The top of the case is equipped with a hinged cover which, when closed, protects the push buttons and the handset. Provision is made for attaching a carrying strap to the case. The over-all dimensions of the telephone are $10\frac{5}{8}$ inches long, $9\frac{1}{8}$ inches wide, and $3\frac{3}{4}$ inches high. Its total weight, including batteries, is about 10 lbs.

The development of this field telephone started in 1956 and was carried on by the Stromberg-Carlson Company under a Signal Corps contract in collaboration with USASRDL audio engineers.[3] A limited quantity of these field Telephone Sets TA-341 ( )/PT are presently undergoing limited service tests as starting and ending links of the associated full electronic-switching communications system, which for the first time makes possible an ideal subscriber's line that carries only voice-frequency currents at voice-frequency communication levels.

[3] R. A. Faralla, C. E. Bessey, J. L. Faherty, and F. D. Vezzosi.

From Eye to Electron—Management Problems of the Combat Surveillance Research and Development Field*

WILLIAM M. THAMES†, SENIOR MEMBER, IRE

Summary—Following an introduction which establishes the fact that increased fire power of modern armies has increased the requirement of those armies for long range combat surveillance and target acquisition capabilities, this article highlights the four basic management problems involved in the combat surveillance R&D field:

1) The initial establishment of relationships with industry, other Signal Corps establishments, other branches of the Army, other Services, and with U. S. CONARC, principal user of the equipment.

2) The development of a logical program.

3) The development of the Combat Surveillance Agency itself as an organization.

4) The development of a technique for monitoring each program and for supervising the agencies, corporations, etc., involved in the various steps of the program.

The solutions that management has applied in order to resolve these problems are discussed in sequence. These solutions include the liaison and information exchange function, a three-pronged program objective, the "systems manager" type of organization and its merits, and a discussion of the "line of balance" chart monitoring system.

Introduction

WHEN the stone age warrior girded his loins for battle and took his flint battle axe from atop his limestone mantle, his eyes and ears were adequate to survey his battle area and to locate the targets against which he wished to use his primitive weapons. Although warriors of later ages devised such new weapons as catapult, sword, and shield, their eyes and ears could still accomplish about all of the surveillance that they required. Even though the observation balloon was used as a means of augmenting the range of the eye in the Civil War, and even though the telegraph found its first military use then, it was not until the twentieth century that the eye and the ear gained the augmentation that we now know as "modern."

When the Wright brothers introduced the age of flight above the sands at Kitty Hawk, and when Lee De Forest ushered in the electronic age with the invention of the vacuum tube, it became possible to design equipment that would give a tremendous increase to the range of the eye and the ear. The airplane enabled the procurement of information many miles in advance of friendly forces. Information so obtained could be transmitted over vast distances by radio.

The last fifteen years have seen enormous advances in weaponry. The rocket has multiplied the range of conventional artillery. The nuclear warhead has raised the lethality of artillery to the fifth power or to the hundredth power; who knows? These advances have not been accompanied by a commensurate capability to locate profitable targets. This made it very clear a few years ago that our Army would again have to augment its means of procuring information of the enemy and its means of locating targets against which to employ newly developed weapons.

In July, 1956, the Chief Signal Officer of the United States Army was given responsibility for developing adequate combat surveillance and target acquisition equipment for our Army at the earliest possible date. This led to the establishment of the U. S. Army Combat Surveillance Agency as a separate activity under the Chief Signal Officer.

The mission of the Combat Surveillance Agency is to direct and supervise the Chief Signal Officer's efforts in all phases of the development of combat surveillance equipment and systems. The Agency is charged with the coordination of the combat surveillance activities of installations and facilities under the control of the Chief Signal Officer. In the discharge of its responsibility, this Agency must provide coordination between the office of the Chief Signal Officer and the combat surveillance activities of other technical services, the DA staff, the Navy, and the Air Force. It must monitor the capabilities of industry to maintain full knowledge of the "state of the art" of a number of fields.

The Department of the Army has defined combat surveillance as "a continuous (all-weather, day and night) systematic watch over the battle area to provide timely information for tactical ground operations." When the Combat Surveillance Agency was established in January, 1957, it soon became apparent that, to produce the equipment that would fulfill this capability, the Agency's efforts would have to enter the areas of radar, infrared, photography, radio and television, and even aircraft and drones.

Fundamental Problems

These fundamental (although interrelated) problems of management faced the agency at the time of its organization:

1) To establish relationships with industry, other establishments within the Signal Corps, other branches of the Army, other services, and with U. S. Continental Army Command, the principal user of the equipment to be developed.

2) To develop a logical program, the fulfillment of which would result in the development of combat sur-

* Received by the PGMIL, July 11, 1960.

† Brigadier General, U. S. Army Combat Surveillance Agency, Arlington, Va.

veillance systems in the shortest possible time.

3) To develop the Agency as an organization that would provide systems managers to supervise the development of each system and to accomplish the many coordinative tasks involved.

4) To develop a technique for monitoring each program. This technique would have to highlight delays early enough to minimize the time that the delays would cost. Such a system would have to reflect at a glance where the delay occurred, who was responsible for it, and the implication that particular delay would have on other activities taking place within the program involved.

Relationships

The first problem that is enumerated above was simplified by three considerations. First, when the Chief Signal Officer selected the key personnel of the Agency, he chose several individuals who had broad backgrounds in the research and development field. These men, although they might be swimming in a new pond, were used to the water.

Second, the mission of the Agency lent clear definition to the relationships that were to be established. Fig. 1 shows the relationships as they have evolved. Third, the establishment of relationships by the Agency was greatly facilitated by widespread appreciation, both in industry and throughout the military establishment, of the necessity for the development of an adequate combat surveillance capability. Since the Agency was the focal point of this research and development field, the path of coordination became a two-way street.

Program Development

You don't swallow an apple—you take bites out of it. Because we had no adequate combat surveillance equipment and because we needed such equipment, however limited it might be, as soon as possible, we established rather unconventional general program objectives for the Agency. These objectives were "unconventional" because they differed from the normal procedure of placing new equipment in the hands of troops. We had to do this because we had no previous generation of equipment. The Army was in a position like that of the original artilleryman who had had no previous catapult to guide him in the design of a new one. Our program objectives (Fig. 2) were:

1) As rapidly as possible to provide the Army with the best equipment presently available or in the final stages of development. Attainment of this capability gives field commanders an increased intelligence capability, increases effectiveness of tactical units as a result of this increased intelligence capability, provides tactical units with experience and training, and provides a basis for the development of future equipment. We have now attained this objective.

2) To develop an advanced interim capability in the

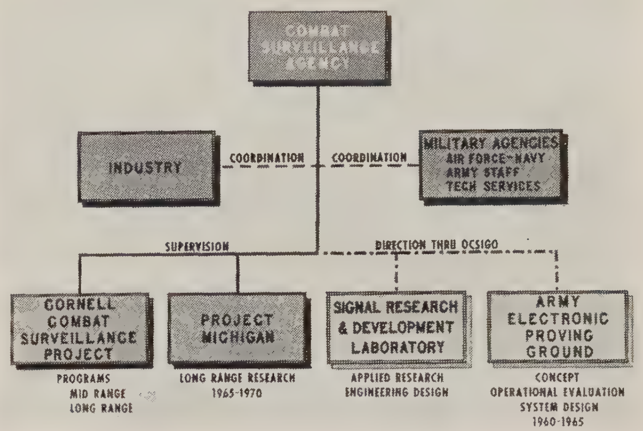

Fig. 1—Surveillance organization.

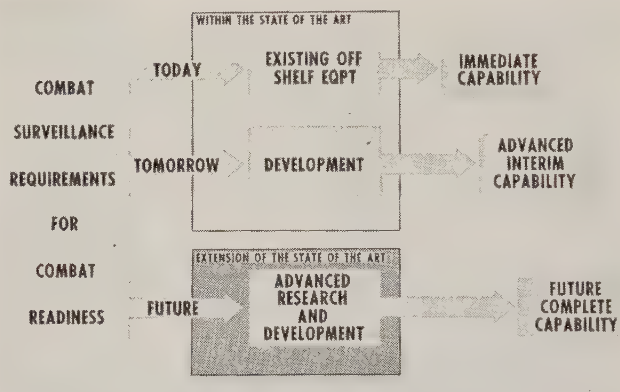

Fig. 2—Technical program objectives.

mid-range time period by using the best techniques that the state of the art allows. The culmination of work that has been in progress for many months will result in the fulfillment of this objective and will provide equipment and systems for the 1962–1965 period.

3) To pursue research and development activities vigorously with a view to advancing the state of the art and exploiting technical breakthroughs that occur. Accomplishment of this objective will provide the Army with a highly effective combat surveillance and target acquisition capability by about 1970.

Organization

Essentially, military organizations can be organized in one of two fashions. They can be organized functionally, under which system a subordinate division is charged with responsibility for the accomplishment of specific functions, or they can be organized along the lines of "product" responsibility. The latter organization is generally preferable to organizations working in the research and development field.

The Agency is organized under the "product" or "systems manager" type of organization. Under this organization, an individual is charged with the responsi-

bilities for the management of a system throughout its development. By overseeing all details involved in the development of this system, by overseeing the accomplishment of all of the functions involved in the development of this system, the systems manager serves to expedite a developmental program to the fullest possible extent.

To give an idea of the "across the board" activities of the systems manager: he may be required to coordinate certain aspects of research being conducted by Project Michigan, in conjunction with an envisioned surveillance system. He may later (or concurrently, for that matter) be required to coordinate with the laboratories at Fort Monmouth, N. J., concerning additional research or concerning a contract or subcontract that has been let by the laboratories in conjunction with the system. He will be required to coordinate matters pertaining to engineer tests of the system, and this may involve coordination with the U. S. Army Electronic Proving Ground at Fort Huachuca, Ariz. He will be required to coordinate matters concerning his system with the Research and Development Division and the Procurement and Distribution Division of the Office of the Chief Signal Officer.

The point to be demonstrated about the systems manager form of organization is that the systems manager is charged with the coordination of all matters of the system under his responsibility.

Program Monitoring

To coordinate and direct the combat surveillance activities of the Cornell Aeronautical Laboratories, Project Michigan, the U. S. Army Electronic Proving Ground and the U. S. Army Signal Research and Development Laboratory, as well as the contractors and subcontractors involved, it was necessary to develop a standardized method of monitoring each combat surveillance program. Because it was not feasible for management to review and analyze the entire history of a system under development each time a policy decision was required, standardized line of balance charts were instituted for each program. These charts are standardized in their technique of data presentation and are prepared for all programs undertaken by the Agency.

The value of these charts as a management tool is threefold:

1) They clearly portray progress in each phase of research and development and in the engineering and service test phases of individual projects. Simultaneously, they provide pertinent funding status information.

2) They provide a visual concept of these programs, for briefing appropriate high authorities on the current status of the Army combat surveillance research and development effort. In addition, they provide a ready means of portraying supporting fund information.

3) They serve as a historical record for the Agency.

To prepare a realistic schedule of the development of a complex surveillance system, advantage must be taken of every available source of information. In addition to the military and civilian agencies under the supervision of the Combat Surveillance Agency, we procure information that is essential to our management activities by liaison with the arms and services of the Army, the Air Force, the Navy, the Marine Corps, and industry. Those members of the Agency engaging in this liaison acquire an intimate knowledge of all phases of their work and constantly increase the value to management of their recommendations.

Drones, for Example

Because it is one of the more glamorous achievements of our activity to date, I would like to highlight some of the managerial aspects of the surveillance drone program. The program grew from the need for extended surveillance and target acquisition involving penetration of heavily defended air space over enemy territory. It has been apparent for some time that the high performance unmanned drone, with its inherent courage, is a logical vehicle for such surveillance.

To envision, to implement, to direct and to coordinate a program of drone development presents many managerial problems. For example, the differing surveillance requirements of battle group, division, corps, and army suggest that design programs must be initiated for drone systems of different endurance and payload capabilities. If programs are to result in the production of modern equipment, equipment that is consistent with the state of the art at the time of its issue, these programs must be planned in terms of the mid- and long-range time periods as well as the present. Additional problems in developing a drone system involve guidance and control systems, navigation systems, and such sensors as cameras, radar, infrared equipment, and television.

Among the drone systems that we have currently programmed, even the interim systems require a constant pushing back of the state of the art curtain. This involves technological break-throughs in both basic and applied research. Managing and directing the implementation of these and other programs must take into account the large number of items and subsystems involved. Extension aids enable the review and analysis of the programs concerned as it is necessary.

Major Programs

The managerial aspects of drone system development are paralleled in the other surveillance systems that are under development. High-resolution airborne radar equipment, infrared scanners, light-weight inertial navigation systems, and ground surveillance radar are among the other major programs with which we are presently concerned.

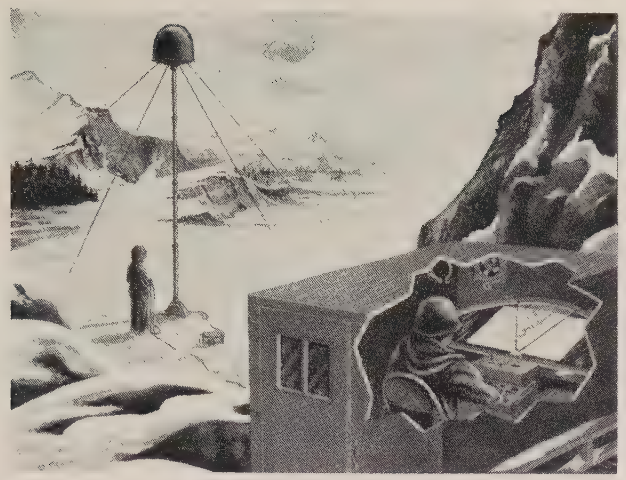

Fig. 3—Radar AN/TPS-25.

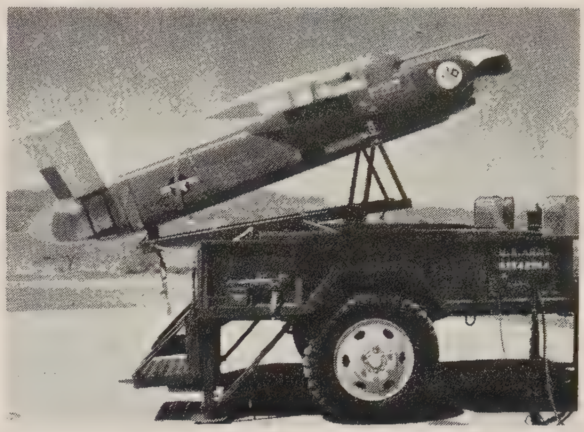

Fig. 5—SD/2 on launcher.

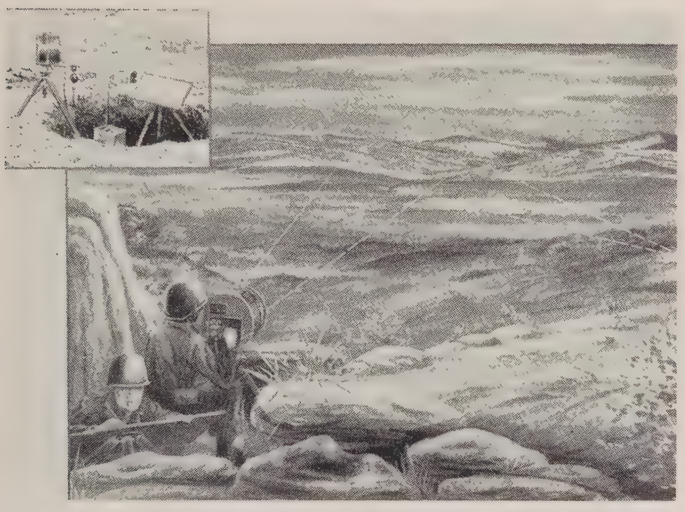

Fig. 4—Radar AN/PPS-4 (night).

With the support of the Army Electronic Proving Ground, the Army Signal Research and Development Laboratory, Project Michigan, and the Combat Surveillance Project of Cornell Aeronautical Laboratory—and with the cooperation of U. S. industry—the Combat Surveillance Agency has made significant progress toward the development of an adequate combat surveillance and target acquisition capability within the U. S. Army. Effective management of our development program is now providing reliable equipment. Further development of this equipment will provide for the surveillance demands of our Army. Combat surveillance remains, however, a field of challenge to management, not only within the Army but also within research institutions of the United States and within American industry.

The Problem of Combat Surveillance*

HERBERT A. NYE†

Summary—**Some of the characteristics of modern warfare which contribute to the difficulty of combat surveillance are summarized. Functions required of modern combat surveillance and techniques of performing these functions are outlined. The role of the Signal Corps in combat surveillance development is discussed, and current developments in combat surveillance are discussed, with particular emphasis on problem areas.**

* Received by the PGMIL, July 11, 1960. This is an adaptation of an article which appeared in the Fall, 1959, issue of *Research Trends*, published by Cornell Aeronautical Laboratory, Inc. of Cornell University.

† Director of Combat Surveillance Project, operated in Arlington, Va., by Cornell Aeronautical Lab., Inc., Buffalo, N. Y.

THE last days of July, 1861, found the Union on the brink of disaster. When McDowell withdrew from Manassas, he left a strong, threatening Confederate force in the area. There was good reason to believe this force would attempt to occupy the Capitol. Washington's defenses were marginal at best. The northern side of the city was virtually unprotected. Should the Confederate forces move up the Potomac, effect a crossing into Maryland, and attack by surprise from the north, Washington would be lost. Movement of the Confederate forces either directly toward Washington or up the Potomac would indicate an attack, and knowl-

edge of any such movement was vital to the defense of the nation's capital. It was during these dark days following the first Battle of Bull Run that Thaddeus Sobieski C. Lowe arrived in Washington with his balloon.

Lowe was received in the White House, where arrangements were made to finance a demonstration. He filled his balloon from the city gas main, hired a telegraph operator, and made an ascent. From a position 500 feet above Washington, Lowe telegraphed Lincoln, and reported that his view commanded a 50-mile circle.

The following day, Lowe made an ascent from the White House grounds. Then, at the request of General McDowell, he made a surveillance ascent on the Virginia side of the Potomac, which resulted in a good map of the Confederate camp. The problem of preventing a surprise attack on the Capital was solved, and Lowe was hired as a military aeronaut. Throughout the fall and winter, balloon ascents along the Potomac kept the Confederate forces under surveillance, while McClellan directed the bolstering of Washington's defenses. The following spring, balloon observers reported the withdrawal of rebel forces from the Manassas area.

Use of surveillance balloons in the Civil War provided a new solution to an old, old problem. The need to know the location of the enemy, his disposition and strength, and his movements, is as old as war itself. Responsibility for the operation of surveillance balloons was assigned to the U. S. Army Signal Corps in 1863. Today, the development of a combat surveillance capability adequate to the needs of the modern army is a primary responsibility of the Signal Corps.

The introduction of missiles and nuclear warheads into the arsenal and the innovations in tactics which new weapons permit or require, have focused attention on combat surveillance as one of the most important problems facing the U. S. Army. Commanders at each echelon must be provided with data on the battlefield situation in sufficient detail, of sufficient accuracy, and with sufficient rapidity to form the basis for effective tactical plans and decisions. In order to make effective use of weapons available to the different commands, each level of command must be provided with a surveillance capability commensurate with the range of its weapons.

The importance of the combat surveillance problem is particularly evident when considering the employment of nuclear weapons in military operations. In such operations timing will be critically important. Army units will attempt to move rapidly on the ground, and will possess some integral capabilities for air transport. Targets will become more fleeting. Camouflage and movement at night and in bad weather, to circumvent air attack, will become more common. The timely location of target coordinates under these circumstances and, conversely, the need for a shifting defensive posture will require more dynamic actions and decisions, and consequently, more rapid, complete and precise intelligence. Also, the enemy may possess more precombat information, making a capability for rapidly obtaining information during combat more important.

The need for an improved combat surveillance capability applies equally to the limited war with conventional weapons. Our Army is committed to a dual capability; this must be and is reflected in currently evolving tactics and organization. Because of the nature of the threat, the Army must possess strategic mobility, as well as a tactical mobility, to permit rapid intratheater movement of troops and supplies. The classic roles of tactical aviation for close support and reconnaissance will pass, at least in part, to surface-launched missiles and to surveillance systems organic to the ground forces.

One of the important functions of combat surveillance is the timely and accurate determination of the coordinates of potential targets for available weapons, including both conventional artillery and missiles. Meeting the precise requirements of target location presents some of the most difficult technological problems of combat surveillance.

Another important surveillance function is that of intrusion detection. Current concepts of the battlefield of the future envision widely dispersed forces. Maintaining the integrity of such forces will be difficult. Combat surveillance must provide protection against enemy infiltration.

Another function completely new to warfare is that of nuclear surveillance. All nuclear detonations, both hostile and friendly, must be detected and assessed. This information, together with meteorological data, will aid in the protection of friendly forces as well as in damage assessment of both friendly and hostile deliveries.

All these surveillance functions will be rendered more difficult by the high degree of mobility the enemy may be expected to possess. Profitable targets may remain profitable only briefly. The enemy situation as seen or sensed at a given time may change completely in minutes. Information which is to provide the basis of appropriate tactical decisions must be presented to the commander with an absolute minimum of delay. Appropriate processing and dissemination of the vast quantity of data accumulated by surveillance sensors is thus vital to effective combat surveillance. Surveillance information must be presented to the particular commander who requires it, at the time he requires it, and it must be presented in a form meaningful to him. The information-processing problem would be challenging even with only the existing information gathering capability. The data-gathering capability currently under development makes the problem truly difficult. The information-processing complex must exploit the capabilities of both men and machines. It must be matched at one end to the data gathering capability of surveillance and other intelligence sources, and at the other end to the basic information requirements for command decision.

The list of candidate sensors for combat surveillance is long, and includes optical aids, photography, television, passive and active infrared, radar, flash- and sound-ranging sets, and seismic and acoustic devices. Sensors alone, of course, do not provide an information collection capability. While examples exist of each of these sensors designed for use on the ground, airborne surveillance systems are necessary to provide depth of coverage. Even in forward battle areas, airborne systems are needed to overcome line-of-sight limitations, to permit wider coverage, more flexible operations, and most particularly, to enhance the target location capability.

The advantages of aerial platforms for surveillance purposes have long been recognized. Surveillance balloons were used not only in our Civil War, but in the Franco-Prussian War, and in World War I as well. Manned kites used in World War I permitted observation of the enemy through powerful glasses from heights up to 2000 feet. General David Henderson[1] emphasized the need for aerial surveillance in this way: "The inventions of modern science, as adapted to warfare, have hitherto tended to loosen the control of a commander over his troops in battle; the perfection of long-range weapons has caused such dispersal of troops that even with improved methods of communication, it has been impossible for commanders to keep themselves thoroughly informed of the position and condition of their forces in action. The aeroplane has altered all this; there is now no reason why a chief commander should not have the same knowledge of the progress of an action, even if his battle line be 50 miles long, as Wellington had, and used so decisively at Salamanca." These words, written prior to World War I, have a familiar, contemporary ring.

While there is a role for manned aircraft surveillance systems, unmanned systems must receive special emphasis. For close-in surveillance, such systems must be designed for simplicity and for the minimum logistics and maintenance necessary for equipments to be used at low levels of command; otherwise, the responsiveness to the surveillance needs of their command levels of airborne surveillance organic to the Army will be illusory. Unmanned systems for surveillance deep in enemy territory are also needed when intensive hostile air defense precludes manned aircraft operations; drones used in this application must have performance compatible with survival.

Substantial progress has been made in the past few years in all areas of sensor technology. Especially worthy of mention are airborne radar, photography, infrared and low-light-level television. Promising methods of nuclear surveillance have been developed. Both manned and unmanned airborne surveillance systems including a variety of sensors have been developed and

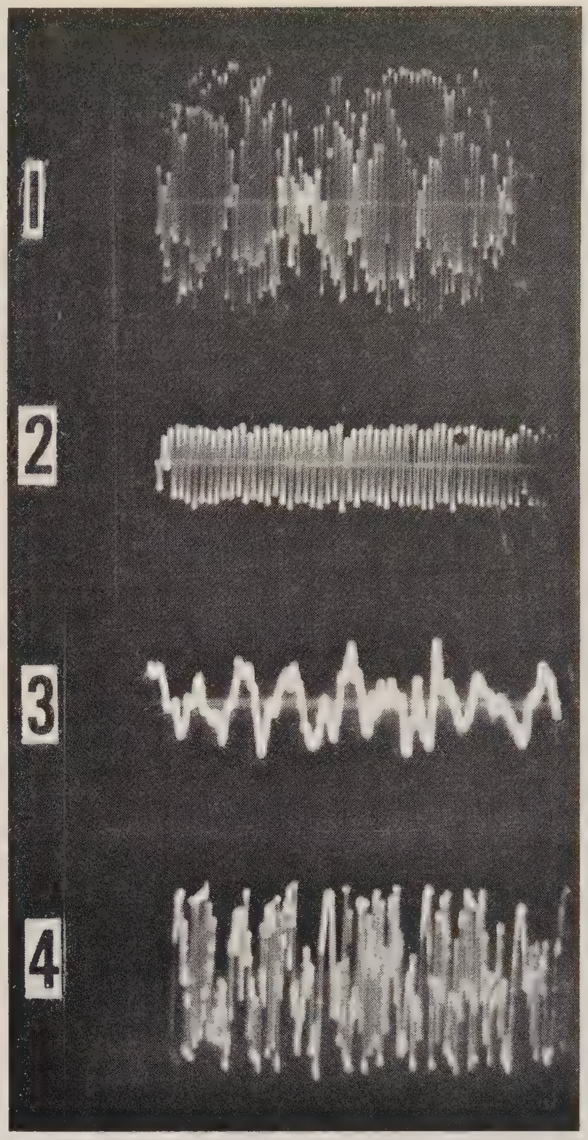

Fig. 1—Typical images displayed on TPS-25 ground surveillance radar. Shown are target images of: 1) a train, 2) an automobile, 3) a walking man, and 4) a walking girl. (U. S. Army photograph.)

tested. Mr. Lowe's balloons, of course, have been replaced by airborne platforms beyond his dreams; just as his field glasses have been replaced by more versatile sensors. Similarly, compass bearings and the visual estimate of range have given way to other techniques for locating objects of interest; and the air-ground communication link is no longer a combination of telegraph, signal flags and the process of attaching messages to rings and sliding them down the balloon anchor ropes.

As a specific example of recent technological advance, the Project MICHIGAN high-resolution radar is an interesting and significant development. Airborne radars, while offering the distinct advantage of increased range to horizon, have in the past provided relatively poor resolution because of the limited physical size possible in airborne antennas. The University of Michigan radar makes a small antenna perform like the exceedingly long antenna necessary for high resolution, by exploiting the aircraft's forward movement, and by using a special data

[1] Brig. Gen. D. Henderson, "The Art of Reconnaisance," John Murray, London, Eng., p. 181; 1914.

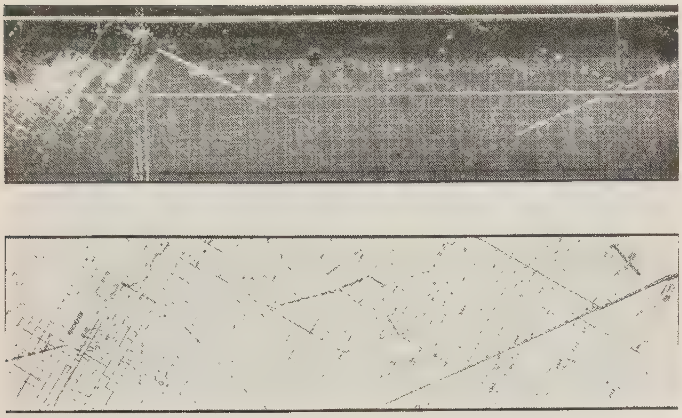

Fig. 2—Above, Radar map of moving traffic in Phoenix, Ariz., made by an airborne radar capable of discriminating between moving and stationary targets. Below, corresponding street map of the same area.

processing technique in which returns are stored and processed to obtain the resolved target image. This system, in effect, also provides a resolution independent of range.

Another development with potential military applications is that of an image orthicon which operates at extremely low light levels. This device, by integrating the light reflected from its subject over a brief period of time, can provide a clear televised image of a scene in almost total darkness.

These examples are illustrative of the numerous advances which have been made in recent years in technologies applicable or potentially applicable to surveillance. What, then, are the major problems today confronting those attempting to provide our Army with an improved surveillance capability? Intensive research and development can undoubtedly yield sensors of greater sensitivity and improved resolution, navigation systems of greater precision and accuracy, airborne surveillance vehicles of higher performance or lower cost.

Of equal importance to these technological problems are those of "systems analysis." The problem of target acquisition can serve as a first example of a serious problem for systems analysis. Target acquisition involves more than the determination of the coordinates of targets with an accuracy sufficient for effective delivery of appropriate warheads. Target acquisition implies detection and identification, as well as target location. Conceivably, there will be instances in a future war in which this will be a simple matter of one, two, three. Such an instance can be expected to be somewhat of a rarity, however; the more general situation being one in which detection and identification each result from a complex but rapid analysis involving indicators and signatures from more than one source or sensor. The process by which targets for the new missiles will be found must be better understood before it can be known with any certainty that the surveillance and the target-location systems currently under development will provide a sufficient capability.

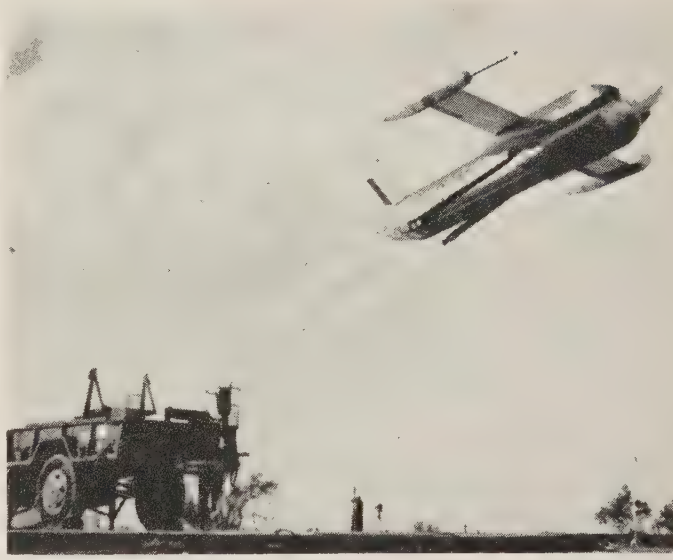

Fig. 3—The USD-2 Drone, one of several pilotless surveillance vehicles now under development.

Fig. 4—Aerial photograph taken from the USD-2 Drone.

A second problem in systems analysis is that of providing proper guidance to a long-range program for combat surveillance. The military strength of our nation depends upon how intelligently we apply our technology. Since not all of the ideas that engineers and scientists dream up can be carried to completion, a process for the selection of new weapon systems to be developed, and the exploratory research to be undertaken, must be established. Limited funds and technical manpower require that the combat surveillance program be properly focused.

This problem, of course, is not unique to combat surveillance. In many areas, however, such as those of continental air defense or strategic retaliation, the mission to be accomplished can be stated much more readily in terms which permit a quantitative comparision of alternate technical approaches to the problem. The greater difficulty in doing this for combat surveillance does not decrease the need to find a way to perform comparative evaluations of proposed alternate systems prior to the launching of expensive development programs, and to establish, on the basis of such evaluations, criteria to be

used in guiding long-range research. This evaluation problem is far from solved, but, fortunately, it is now beginning to be recognized and understood, and some proggress is being made.

The increased pace of technological development is reflected in the rapid evolution of new military tactics. It is important that our surveillance capability keep pace with weapon potentials and with the tactics reflecting these weapon potentials if the adequacy of combat surveillance is to be maintained. The many technologies which can contribute to combat surveillance are wen vanced. The current development program is designed to exploit this advanced state of the art as fully as is now possible. In anticipation of operational experience to be gained with the products of this development program, and with the study of effects of combat surveillance techniques through war games and other types of analysis, the Army can look forward with confidence to a combat surveillance capability adequate to its needs in this atomic age.

Radar in the Signal Corps*

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Summary—**The accomplishments of the Signal Corps Laboratories in the development of radar are described with emphasis on the pre-World War II period. The development and evolution of early warning radar and fire control radar in the Army are treated in some detail. The ground radars used in combat during the war by the Army (including the Army Air Corps) are discussed.**

SIGNAL CORPS research and development in the field of radar predates the word RADAR itself. In fact, in the Army, what we now call Radar was initially known as radio position finding. Development work on the pulse method of radio location started at the Signal Corps Laboratories, Fort Monmouth, N. J., in the early 1930's. A small group of engineers and physicists, headed by early Laboratory Director Lt. Col. Blair, Maj. Gen. (then Lt. Col.) Roger B. Colton, and Civilian Chief Engineer (later Lt. Col.) Paul E. Watson labored under great secrecy on the concept of locating aerial targets by means of radio waves. These pioneers worked in silence, desperately handicapped by lack of personnel and funds but inspired by visions of a great new weapon which would do much to protect our nation against the growing air power of our potential adversaries.

The pioneering development progressed to the point where it was feasible, in May, 1937, to put on a crude field demonstration for the Secretary of War at Fort Monmouth (see Fig. 1). The equipment performed so well that it unmistakably demonstrated the great potential of this new technique in anti-aircraft defense. The Secretary of War was impressed and decided that this new technique should be vigorously pursued. The Coast Artillery Corps produced a set of military characteristics for a searchlight controller to position and aim searchlights for spotting aircraft. Thus was born the concept of the first Army Radar, Searchlight Controller, Radio Set SCR-268. It is only fair to say that SCR-268 is the original ancestor of all Army and U. S. Air Force radars, remembering that the first U. S. Air Force radar was a modified SCR-268 installed in a B-18 at the Red Bank, N. J., airport.

Fig. 1—Experimental radio position finding equipment—May, 1937.

At this point it should be mentioned that both the SCR-268 and the SCR-270 (early warning radar to be described in this paper) Series of radars had many modifications and conversions adapted to specific applications. (SCR-268-T1, SCR-268-T3, SCR-268, SCR-268-A, etc.). Thus one should speak of an SCR-268 family of sets, all of which were mobile, that is, mounted on trucks or trailers. Similarly, the SCR-270 family were mobile sets while the electronically equivalent radars intended for fixed stations installation were known as the SCR-271 family of radars.

Following the May demonstration, the Signal Corps Laboratories reorganized and formed the Radio Position Finding Section, headed by the Chief Engineer, Paul E. Watson. A small staff of approximately five engineers started the Herculean task of rapidly developing and building a radar which would meet the requirements of troop use. Day and night work, as well as Sundays, was the usual thing (no paid overtime in those

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days). Such was the enthusiasm of this small group that by early January, 1938, a further demonstration at Sandy Hook of a more or less embryo model was given for the Chief Signal Officer, and this firmed the planning for the initial SCR-268 which was subsequently service tested late in 1938 at Fort Monroe, Va.

This development work had advanced the state-of-the-art to the point where the stage was set for a somewhat different radar application, namely, a powerful early warning radar. The initial effort associated with this latter set was carried on to a great extent behind the scenes and after hours, inspired and guided by Mr. Watson. There were no MC's for an early warning radar nor was there the powerful support of the Coast Artillery Corps which was sponsoring the SCR-268. Such sponsorship meant badly needed funds.

During the first half of 1938, a few engineers were added to the small staff of the Radio Position Finding Section. Early in the summer, Lt. Col. Roger B. Colton, who had been Executive Officer of the Laboratories a few years before, returned to the Laboratories as Director. Col. Colton added his inspiration and drive to the entire radio position finding program and ordered full steam ahead on the early warning radar development, in addition to the accelerated activity on the SCR-268 searchlight controller development.

Parallel effort was placed on the two developments, Early Warning SCR-270, and Searchlight Controller (leading to Fire Control) SCR-268. I shall describe first the SCR-268 effort and then return to pick up the early warning development.

The success of the 1938 service test of SCR-268-T1 (Fig. 2 shows the principal components) at Fort Monroe led to a redesign and approval for production. The SCR-268-T1 used in the service test was a "three mount design," *i.e.*, the transmitting, azimuth and elevation antennas were placed on separate mounts. The redesigned SCR-268 which went into quantity production used a single mount for the three antennas (see Fig. 3). There were a number of other improvements incorporated but pressure of time caused a quick freezing of design.

A contract for production engineering and production quantities of SCR-268 was consummated in midsummer 1940 with the Western Electric Company as prime contractor. Deliveries of finished radars commenced in February, 1941. Eventually some 3100 of the SCR-268 series were produced. A tabulation of the principal characteristics is shown on Fig. 4.

When Pearl Harbor was attacked, the U. S. Army had in existence quantities of only two basic radars, the SCR-270-271 Early Warning Radar, and the SCR-268 Searchlight Controller (also adapted and used for AA Fire Control with moderate success (see Fig. 5). At this time, the main effort of the Signal Corps Laboratories was redirected from further development to production of radars. Only a very limited effort on development and modification improvement remained with the Signal Corps Laboratories. However, Radiation Laboratory, already active in radar development, was given the task of pushing radar development. One of the first products of Radiation Laboratory was the experimental XT-1 which arrived at the Signal Corps Laboratory test site at Fort Hancock, N. J., in December, 1941. The Signal Corps Radar Laboratory (new name for expanded Radio Position Finding Section of Signal Corps Laboratory), Fort Monmouth, was charged with the production engineering and procurement of the fire control radar, now called SCR-584, which (when it became available) would displace SCR-268. Two production contracts were placed, one with General Electric Company and one with Westinghouse Electric and Manufacturing Company. During 1942, the Signal Corps Radar Laboratory struggled with the production engineering problems of the components of SCR-584. It was mid-1943 before initial sets were delivered (see Fig. 6). Eventually about 1570 sets were delivered. SCR-584 played an important role in defense against the buzz bomb (V-1) in England in late 1944, and at Anzio Beach where it began to replace the SCR-268. Numerous modifications have been made on the basic SCR-584, adapting it to many uses. To cite just one example, the modified 584 and derivatives thereof carried the load of missile tracking at the White Sands Missile Range, N. Mex. for many years. To this day, modified 584's still exist. This was truly an excellent radar.

I shall now return to 1938 and pick up the early warning development. This early work had clearly shown the great need for more powerful transmitting tubes. In fact, the lack of suitable high frequency vacuum tubes was probably the biggest single bottleneck limiting the development of radar at this stage. This was true at 110 Mc frequency (SCR-268 started on 110 but wound up at 205 Mc; higher frequency to permit smaller antennas). It was even more true at 205 Mc and higher with almost nothing in existence above 400 Mc. Tube development had to be pushed. Several parallel programs were initiated to develop a suitable transmitter tube.

The requirement of mobility for fire control equipment forced the operating frequency of SCR-268 to 205 Mc. The growing requirement for a long-range radar to provide early warning information to interceptor squadrons provided impetus for the development of SCR-271 (fixed station) and SCR-270 (mobile) radars. The plans called for a high-powered tube on 110 (approximately) Mc. This requirement was met by the Westinghouse development of the water-cooled WL-530 tube—a tube, representing by the way, the first major contract of any kind in this new field.

By midsummer of 1938, the early warning radar program was advancing rapidly with Col. Colton guiding and aiding by day and night, as only Roger B. could do.

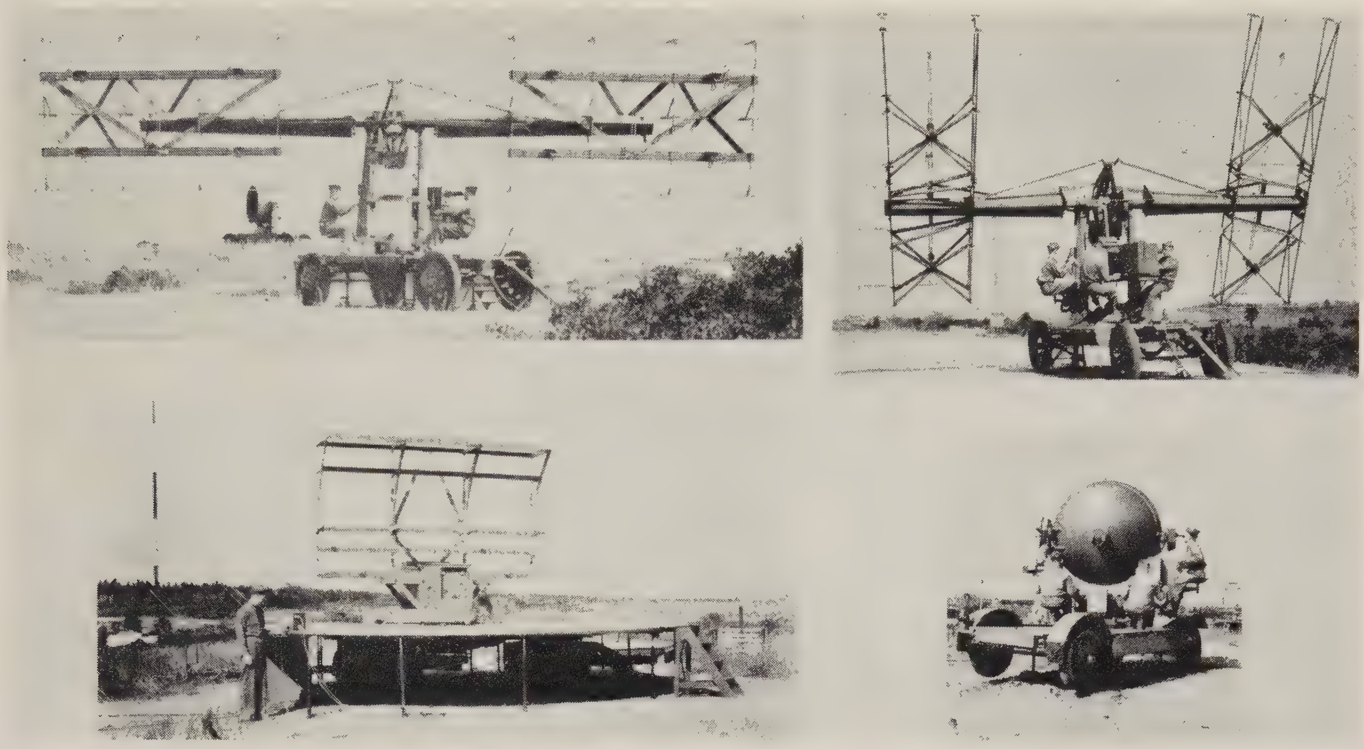

Fig. 2—Components of SCR-268-T-1 at Fort Monroe.

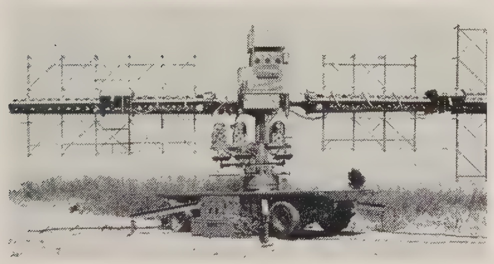

Fig. 3—SCR-268 (single mount).

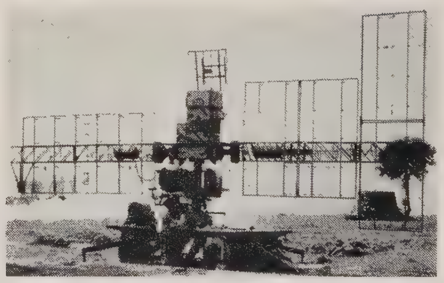

Fig. 5—Radar and anti-aircraft battery operating with Fifth Army in Italy—SCR-268B.

Frequency (Mc)	195–215
Peak Power (kw)	75
Pulse Length (μsec)	5
Pulse Rate (PPS)	4098
RF Source (16) Eimac	100TS
Antenna:	3 separate dipole arrays with reflectors.
	Transmitting—4 wide by 4 high.
	Azimuth Receiving—6 wide by 4 high Beamwidth—12°
	Elevation Receiving—2 wide by 6 high Beamwidth—9°
	Azimuth and elevation antennas split for lobe switching.
Indicator:	Range 5-inch A-scope
	Azimuth 5-inch A-scope
	Elevation 5-inch A-scope
(Approximately 3100 sets were built.)	

Fig. 4—Tabulation of SCR-268 characteristics.

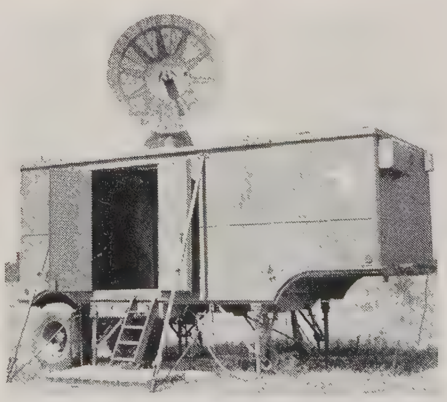

Fig. 6—Radio set SCR-584.

A new site for this activity had been found, the Twin Lights Area in Highlands, N. J., overlooking the ocean and scene of some of Marconi's early experimental transoceanic broadcasts. By mid-August, an experimental model of the SCR-270 was assembled at Twin Lights and readied for a demonstration on an actual bomber flight. This took place on one of those terrible, hot August afternoons. Chief Engineer Watson, the designer of the transmitter, expressed great confidence in our new setup, stating that we would detect the bomber at at least 65 miles, but Col. Colton was a bit skeptical as to the range.

Well, the demonstration started. The usual number of mishaps which one gets with haywire equipment happened. The receiver front-end burned out. A replacement receiver was rapidly put in place while the other one was repaired. But with it all, a continuous track of the outgoing plane was visible on the scope—out to beyond 70 miles. After continuing a while, the pilot was requested by radio to fly in a circle. There, at a range of 78 miles, stood the echo clear and unmistakable. The embryo 270 had demonstrated its great capability and the push was really on to get a set that could be put in the hands of troops.

By October, 1938, Westinghouse had delivered samples of the WL-530 tube (water cooled). Concurrently, the efforts of Dr. Harold A. Zahl resulted in a high-power vacuum switching tube which made it possible to connect the high-power (100 kw peak power) transmitter using the WL-530 tube to a common antenna with a sensitive radar receiver. Fig 7 shows some of the early equipment in position at Twin Lights. The turret-like tower in the background was used as a laboratory for work on components.

By June, 1939, an engineering model of SCR-270 was being flight tested at the Twin Lights location with fairly consistent tracking of aircraft out to 80 miles and occasional detection as distant as 150 miles. A system setup was then assembled with a pair of SCR-270's, one at Meriden, Conn., the other at Twin Lights, and a control center at Twin Lights. This system was demonstrated during November, 1939, and used to detect and track a flight of B-17's from Mitchel Air Base out to the end of Long Island (138 miles) and back. The demonstration was witnessed by Secretary of War Woodring and Generals Marshall, Arnold and Mauborgne. It was dramatic and successful.

By the end of 1939, the SCR-270 had truly proven its worth as the first early warning Army radar and it was adopted by the Army in May, 1940. A contract for a production quantity was given to Westinghouse in August, 1940. Prior to this time the fabrication, as well as the development, had been done at the Signal Corps Laboratories with the assistance of contractors on the manufacture of individual parts and components. On the new contract, Westinghouse would apply its own production engineering to the various parts but were not required to do further development. From laboratory model to first production delivery required only six months, a remarkable achievement for both developer and manufacturer. The contractor delivered 112 sets prior to Pearl Harbor day. Fig. 8 shows a Westinghouse manufactured SCR-270B in transport position.

The first Signal Aircraft Warning Company was formed for service in Panama in January, 1940, and a second for service as part of the Northeast Air Defense Command in February, 1940. The fabrication of a fixed station version of the long range radar, SCR-271, was started early in 1940 and two of these sets were shipped to Panama in June, 1940. One of these sets, put into operation at Fort Sherman in June, became the first radar in the American defense system (see Fig. 9).

Fig. 7—Early experimental models of SCR-270 and SCR-271 at Twin Lights, N. J.

Fig. 8—Components of SCR-270B in transport.

Fig. 9—SCR-271 Radar Station at Fort Sherman, Panama.

A number of SCR-270's were shipped to Hawaii in the latter half of 1941. There were six mobile stations spotted around the perimeter of Oahu in early December, 1941, the one at the northern most tip being known as the Opana Station. During this period the radars were being operated each day only during the three hours considered most dangerous, namely 0400 to 0700. This short period was ordered in order not to risk burning out the radars for which there were precious few spare parts in the Department of Hawaii.

On December 7, 1941, there were only two men on duty at Opana; the third (normally there) had been given a pass to go to Honolulu. Standard operational procedure called for shutting down the station at 0700. The two men on duty, Pvts. Lockhard and Elliot, had seen nothing unusual during their three hour tour. The truck, due to take the two men back to Camp, was a bit late so Elliot, new at the job, suggested he practice a bit with the radar under Lockhard's supervision. At 0702, an echo appeared on their scope such as neither of them had ever seen before, large and luminous, at 132-mile range.

Something must be wrong with the equipment—but it wasn't. By 0720 the two men decided to report to the Information Center at Fort Shafter. Well, the rest is history—how this detection of the Japanese attack went unheeded and the war was on. It is not the purpose of this article to discuss this controversial day.

At this point it may be well to digress for a few words on comparisons between American and British early warning radars, since this was a subject of much controversy in the early war months. The capabilities and limitations of radar in general were poorly understood in this early period. The British, under the terrible pressure of actual war, had become adept and skillful in the use of their radar system and achieved good results. They used fixed station radars in a system well adapted to island defense. Until Pearl Harbor, the U. S. had no comparable pressure or experience in the use of radar equipment, nor had we digested the systems concept in the use of radar. Moreover, the defense of the Continental U. S. posed a much greater problem in terms of quantities of radars required.

Mobile sets were therefore built in order to achieve maximum flexibility of defense, remembering that quite insufficient sets existed for a perimeter defense. However, all too often, comparisons were made which appeared to favor the British CH-CHL Radars. Such radars were therefore imported from England for analysis and comparison in a field set-up at The Signal Corps Radar Laboratory, in Belmar, N. J. The net conclusion was that the SCR-270 as an equipment gave better performance, whereas the British system for presenting and using radar-gathered information was better. The value of PPI (Plan Position Indicator) type presentation (used by the British) had been previously recognized, and steps were already underway to incorporate PPI in future 270's and also to supply it as a field modification for existing installations. The advantage of the PPI display over Type A is its ability to display the direction and range echoes simultaneously, whereas Type A is limited to range only.

During late 1941 and 1942, a network of approximately 25 SCR-270's was installed along the Pacific Coast, with a few in Mexico and Canada, to feed early warning data on aircraft into the various information centers. A similar network had previously been installed along the Atlantic Coast, with stations being added during 1941 in Newfoundland and Iceland. It can, therefore, be seen that by the end of 1941, America had an existing early warning radar system around its perimeter, and that the SCR-270-271 series of radars were the heart of the system.

A number of SCR-270 sets were procured for the Marines, and these sets were used during amphibious operations on Guadalcanal and other Pacific Islands. Marine officers were full of praise for the sets and stated that each SCR-270 was the equivalent of a squadron of planes in the performance of an early warning function. Since planes were scarce at this time, the radar sets were priceless.

In the Fall of 1940, British scientists had introduced their improved magnetron to our defense officials and the decision was made to create Radiation Laboratory (physically at Massachusetts Institute of Technology) for the purpose of developing and exploiting microwave radar. It was further decided that the Signal Corps Laboratories should proceed with all haste into production with our lower frequency radars to gird for the coming war.

Radiation Laboratory proceeded with the development of a microwave early warning radar—initially called MEW, and subsequently AN/CPS-1 (see Fig. 10). This set was produced by the General Electric Company under contract with the Camp Evans Signal Laboratory.

Let me digress just a moment to mention that it was during the preproduction testing of MEW at Tarpon Springs, Fla., in July, 1943, that the value of radar in storm detection became apparent. Every day thunder-

Fig. 10—MEW (AN/CPS-1).

storms were clearly observed as clutter on the PPI scope as they moved in from the Gulf of Mexico. It became possible to predict almost to the minute when the rain would fall on the radar site. This type of clutter, criticized as a nuisance at the time (the lower frequency SCR-270 did not have it) has since been put to good use. (After the war, the Signal Corps developed storm detector radars.)

This set operated at approximately 3000 Mc. This radar, because of its high frequency, could achieve a much narrower antenna beam for a given size antenna. It can, therefore, resolve or distinguish between multiple targets far better than a long-wave radar such as the SCR-270. So the successor to the SCR-270-271 series was in the making—an evolutionary process. However, MEW sets were not put into operation until 1944, mostly in Europe. By this time the threat to the Continental U. S. had subsided considerably.

A few more words on the final course of the SCR-270-271 may be of general interest. To increase the long range capability of the radar, a series of modifications were developed during 1943 and 1944 at the Signal Corps Laboratories resulting in a final version of SCR-271 with the following characteristics: transmitter peak power—500 kw (using the same WL-530 tubes); pulse width—20 μsec; antenna—64 dipoles 8×8 configuration; antenna beamwidth approximately 10°.

This final version mounted on a 400-foot tower at Oakhurst, N. J., succeeded in tracking a single P-51 aircraft out to 270 miles, losing the target only because of the line-of-sight limitations. The U. S. Air Force, as a separate service, took over cognizance of early warning radar in February, 1945. This included the SCR-270 271. Many of these sets were later used for long range meteor detection and various propagation efforts.

The 270 played a part in still another long range effort—another "first!" This program, initiated at Evans Signal Laboratory in 1945 and known as "Diana," used the major components of SCR-271, suitably modified and incorporating the frequency modulation techniques developed by Maj. Edwin H. Armstrong, the equipment succeeded in sending pulses and receiving back radar echoes from the moon in January, 1946. This also is history, and will not be further discussed here. However, it may be of interest to mention that there are now two powerful radars at this "Diana" location which have tracked, and continue to track and communicate with various earth satellites, including TIROS and PIONEER V (see Fig. 11).

The principal technical characteristics of the 270-271 series have been summarized and are included as Fig. 12.

The need for a transportable lightweight Early Warning Radar led to the development in 1942 by Bell Telephone Laboratories under contract with the Signal Corp Radar Laboratory of SCR-602-T-3, redesignated AN/TPS-1A. This set was developed for tactical use by the Army Air Corps and the Marine Corps. It played a significant role in the latter part of World War II. A redesigned version of this set, AN/TPS-1D, has seen many modifications and applications in post war years.

Fig. 11—Diana Radar.

Technical Characteristics

	SCR-270, 270B SCR-271-A	SCR-270-BA SCR-271-D	SCR-270-DA SCR-271-DA	FINAL VERSION (EXPERIMENTAL)
Frequency (Mc)	104–112	104–112	104–112	104–112
Peak Power (kw)	100	100	100	500
Pulse Length (μsec)	10 to 30	10 to 30	10 to 30	10 to 30
Approximate Average Power (w)	2500	2500	2500	2500
Noise Figure (db)	12 db	12 db	6 db	6 db
Antenna (Broadside Dipole Array)	4 wide by 9 high (nonresonant)	4 wide by 8 high (resonant)	8 wide by 4 high (resonant)	8 wide by 8 high (resonant)
Azimuth Beamwidth (degrees)	28	28	11	11
Indicator	5-inch A-scope	5-inch A-scope	12-inch A-scope 12-inch PPI-scope	12-inch A-scope 12-inch PPI-scope

Physical Characteristics

SCR-270	Antenna trailer, prime mover, operating truck, and antenna storage truck.
SCR-271	Original set used building-tower combination 36 feet high with antenna on tower.
SCR-271-D	100-foot tower with antenna plus separate building. (Approximately 800 sets were built.)

Fig. 12—Tabulation—SCR-270 characteristics.

Time and space do not permit describing many other significant Signal Corps accomplishments in the field of radar. To touch lightly on just a few, I might point out that the Signal Corps developed both techniques and equipments for radar detection of mortar shells and location of firing sites, late in World War II. In the Korean conflict, the AN/MPQ-10 Mortar Locator played a significant role (see Fig. 13). This radar was engineered and produced by Sperry under contract with the Signal Corps.

In 1943, the Signal Corps Radar Laboratory (by that time redesignated Camp Evans Signal Laboratory) placed a contract with Gilfillan Brothers for the engineering and production of the first Ground Control Approach Radar. Developed by Radiation Laboratory, this navigational radar known as AN/MPN-1 took its place in the arsenal of Air Force equipment in 1944, and played a significant role in World War II. I could mention, just to pick a few at random, SCR-545, SCR-547, SCR-296, AN/TPS-3, AN/TPS-4, IFF. There were more.

With the end of World War II, the Signal Corps' efforts in the field of radar were redirected into more specialized channels. The U. S. Air Force continued development in the field of early warning and navigation, and the Ordnance Corps proceeded with fire control radar development.

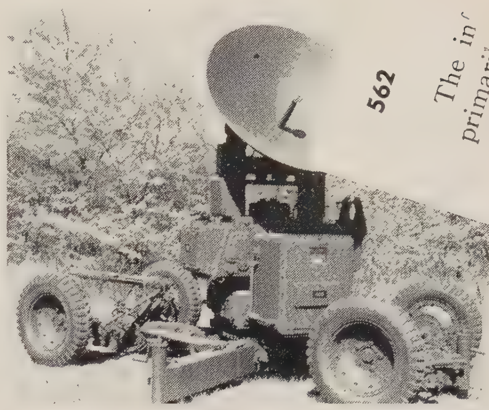

Fig. 13—Radar Set AN/MPQ-10.

The Signal Corps concentrated its efforts largely in the field of mortar location, electronic support of guided missiles activities, and various special developments, in support of other services, such as Meteorological Radar for U. S. Air Force, but by and large for the activities of the Department of the Army.

This paper is not intended to be a comprehensive or exhaustive treatment of all Signal Corps development work in the field of radar, nor is current activity described; rather, it is hoped that the highlights given herein will give some insight into the very important role that the Signal Corps has played in the evolution of this modern miracle—RADAR.

Application of Signal Corps Radar to Combat Surveillance*

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Summary—**The U. S. Army Signal Research and Development Laboratory has developed several types of radar equipment to fulfill the combat requirements of the Field Army. To aid in obtaining an all-weather continuous surveillance capability, the AN/PPS-4 and AN/TPS-25 ground radar sets were developed. To extend and supplement their coverage of the combat zone, the AN/APS-94 airborne radar was developed. Locating weapons of interest is another important function of combat surveillance. The AN/MPQ-4 mortar locator was developed for this purpose.**

Introduction

THE present concept of limited warfare includes combat elements of rapidly moving ground forces. To manage such forces effectively and efficiently under all environmental conditions of weather and terrain, and to do this around the clock, requires that the Army commanders have continuous information available on the whereabouts and numbers of the enemy forces (men, vehicles, weapons and structures), as well as the friendly forces.

The idea of battlefield or combat surveillance has been born out of this current concept, and it is evolving into a new complex of military sensors (electronic and other types), which will have such characteristics and will be so deployed as to gather the surveillance information required. This information includes: the detection and approximate location of personnel, vehicles, weapon sites, and concentrations of troops; the detection of storm clouds and nuclear bursts; the monitoring and storage of position data over extended periods of time on the movement of personnel, vehicles, and aircraft in the combat zones.

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storms ıormation resulting from this surveillance is scope ıy of an intelligence and target location nature, becaıecessary to properly determine future action. It theısists of: the identification and accurate navigation c friendly forces; the accurate location of personnel, vehicles, aircraft and weapons; the registration of friendly weapon fire; the guidance and control of friendly forces; and the tracking and detailed analysis of storm and nuclear burst clouds. To tie accurate location and navigation properly into the combat zone picture on an all-weather continuous basis requires target-position designation in a highly accurate coordinate form. This will require the development of electronic, radar-type long-range area mapping techniques.

The U. S. Army Research and Development Laboratory at Fort Monmouth, N. J., has carried on an active program to develop equipment to form part of this surveillance capability. In the following pages, certain unclassified equipment will be described.

Basic Principle of Operation

In order to apply radar to the detection of targets of interest in the presence of the underbrush and uneven terrain of the battlefield, it was necessary to employ a technique that would be more sensitive to the motion of these targets in comparison to the fixed terrain clutter. The most obvious and practical approach was developed around the Doppler effect, which is an inherent characteristic of all wave motion associated with a source of oscillating energy being transmitted through a medium, when the source or transmitter and listener or receiver are in relative motion with respect to each other. The frequency difference between the transmitted signal and the signal reflected from the moving target, or the Doppler frequency, is $(2v/c)fo$ where v is the radial velocity of the target with respect to the radar set, as shown in Fig. 1.

As viewed at the input terminals of the receiver, the net effect of the clutter produced at a particular range from the radar set, can be represented as the sum of the individual radar reflections (clutter components) coming from the terrain at that range. Since these individual reflections are from fixed objects, the phase and amplitude of resulting clutter vector, as indicated in Fig. 2, will be constant for each successive received pulse. If a moving target is present at the range under surveillance, the signals reflected from it will vary in phase from pulse to pulse, and can be represented as a rotating vector. The total signal will be seen to have an amplitude modulation equal to the Doppler frequency, in the order of 20 to 1000 cps for the radar surveillance sets to be discussed. These sets make use of the Doppler effect and the particular technique of using the clutter signal as the constant phase reference signal as indicated in the figures. This technique results in noncoherent Doppler operation. When clutter is not present to serve as the reference signal, as in the case of airborne targets, a local oscillator can be stabilized with respect to the transmitter and used as the reference signal. This technique results in coherent Doppler operation.

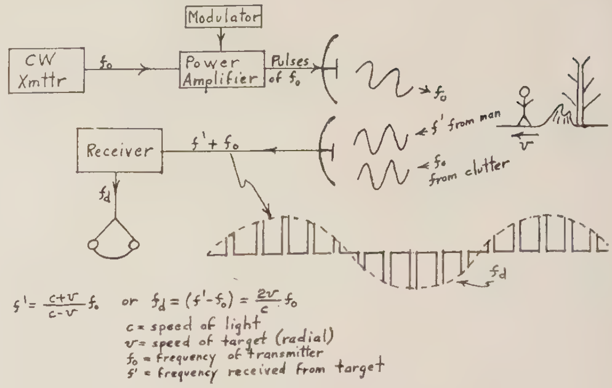

Fig. 1—Doppler effect of radar signal.

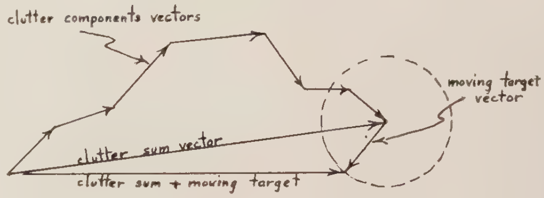

Fig. 2—Vector diagram of Doppler effect.

Discussion of Radar Equipments

The first surveillance radar set to be discussed was evolved from an early development by the Sperry Gyroscope Company, Great Neck, L. I., N. Y. A military specification prepared by the U. S. Army Signal Research and Development Laboratory around this radar resulted in a contract with Sperry for the AN/PPS-4 (known as the Silent Sentry of the Army). A mutual development-testing-evaluation program between Sperry and USASRDL led to the present version of the AN /PPS-4, which is being supplied to the Field Army as the frontline man-pack surveillance radar.

The AN/PPS-4 is a lightweight radar, weighing about 85 pounds complete with power source, capable of being carried by two men and operated by one man. Figs. 3 and 4 show assembled and unassembled views of the radar set. The set tactically shown in Fig. 5 will reliably detect a walking man to 1500 meters and a moving vehicle to 8000 meters with a range accuracy of ± 20 meters. It is manually controlled in azimuth and range, and uses earphones for audio detection of target. Pertinent technical characteristics are listed in Table I. The production version is transistorized and will operate from batteries.

The AN/TPS-25 is the largest of the combat surveillance ground radars. It was procured from the Hazeltine Electronic Corporation, Little Neck, L. I., N. Y., on the basis of a military specification developed by USASRDL in coordination with the Continental Army Command. Its operation is basically the same as the AN/PPS-4, but more complex as indicated in the block

Fig. 3—Radar Set AN/PPS-4 (assembled view of service test model). Over-all $\frac{3}{4}$ view showing complete equipment.

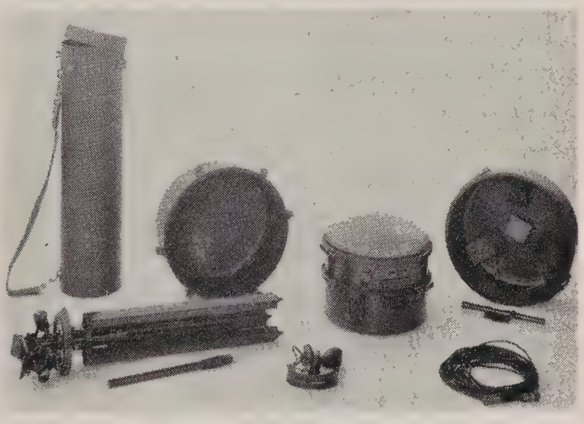

Fig. 4—Radar Set AN/PPS-4 (unassembled view of service test model). Group $\frac{3}{4}$ view showing equipment ready for storing in transit case.

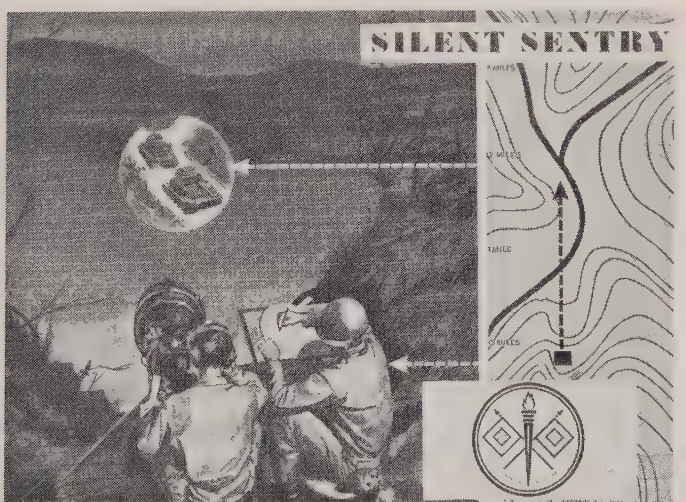

Fig. 5—Radar Set AN/PPS-4 (tactical view).

TABLE I

Pertinent Technical Characteristics

Radar Set AN/PPS-4	
Frequency	8900–9400 Mc
Peak power	1 kw
Pulse width	0.2 μsec
Antenna beam width (azimuth)	6.5°
Range capability	1500 meters (walking man) 8000 meters (moving vehicle)
Range accuracy	±20 meters
Presentation	AGC meter and earphones
Azimuth control	Manual
Power	60 watts (production version)
Weight, including batteries	85 pounds (production version)
Radar Set AN/TPS-25	
Frequency	9375 Mc
Peak power	43 kw
Pulse width	0.5 μsec
Antenna beam width	
Azimuth	10° in search 2° in track
Vertical	4°
Antenna coverage	
Azimuth	180, 360 and 540 mils (automatic search)
Vertical	±265 mils
Range capabilities	4500 meters (walking man) 18,000 meters (moving vehicle)
Range accuracy	40 to 75 meters
Presentation	Visual counters, earphones, plotting board, and cathode-tube A-scope
Power required	1.5 kw (with shelter)
Antenna tower	20 feet long
Radar Set AN/APS-94	
Frequency	9245 Mc
Peak power	100 kw
Pulse width	0.5 μsec
Antenna beam width	
Azimuth	0.5°
Vertical	Cosecant squared
Presentation	
Main readout	Two 5-inch cathode-ray tubes
Film size	4×5 inches or 70 mm
Radar Set AN/MPQ-4	
Frequency	16.000 Mc
Peak power	50 kw
Pulse width	0.25 μsec
Maximum range	10,000 meters
Antenna beam width	
Azimuth	18 mils
Vertical	14 mils
Azimuth scanning sector	450 mils
Antenna beams	Two scanning beams Beam separation—36 mils
Presentation	B-scope (range vs azimuth) Target echo indication—two dots
Computer	Analog (computes weapon location)

diagram of Fig. 6. Fig. 7 shows a tactical view of this set, and Fig. 8 shows an interior view of the operating shelter. The AN/TPS-25 can detect and locate a walking man to 4500 meters and a moving vehicle to better than 18,000 meters with an accuracy of less than 75 meters. In operation, the set searches in azimuth manually or automatically over a selected azimuth sector and over a selected range segment. Upon detection of a target, the antenna is stopped and next the strobing range gate is stopped. The set, now in the tracking mode, uses a narrow antenna beam and is manually controlled in azimuth and range to track the target and obtain target position data. The set also has a capability for registering the location of a bursting artillery shell.

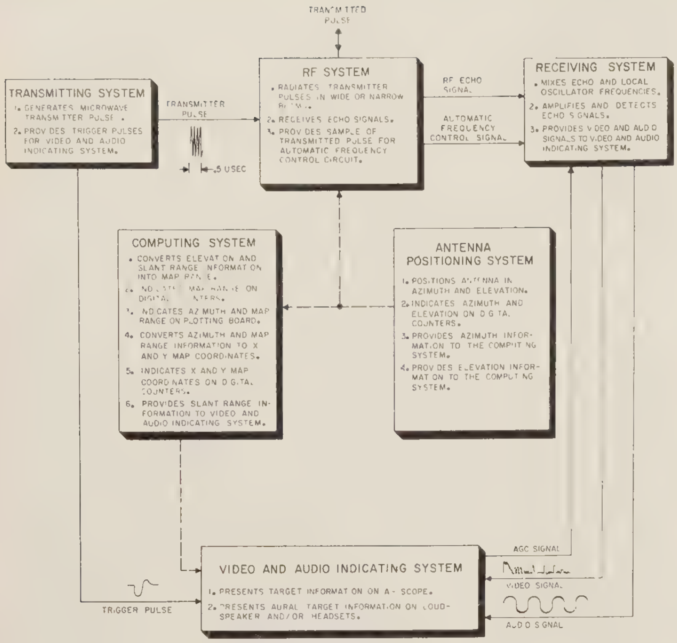

Fig. 6—Radar Set AN/TPS-25 (block diagram).

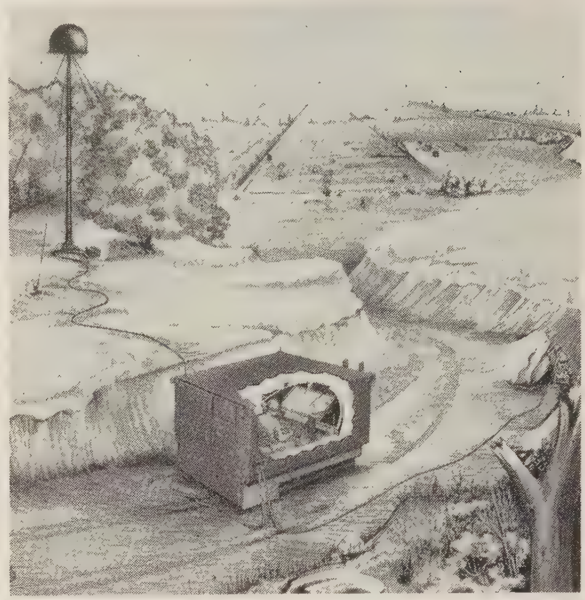

Fig. 7—Radar Set AN/TPS-25 (tactical view).

Technical characteristics of the set are listed in Table I.

The required coverage for combat surveillance extends out beyond the forward edge of the friendly area to a greater distance than can be effectively covered by ground-based line-of-sight radars. As a result, the development of airborne radars for Army use was sponsored as part of a Joint Service contract effort at the Control Systems Laboratory at the Illinois Institute of Technology. USASRDL continued this original effort, and based on the results achieved with the first experimental model, contracted with the Motorola, Inc., Western Military Electronics Corporation, Scottsdale, Ariz., for service test models of the AN/APS-85 side-looking airborne radar, and a later improved version, the AN/APS-94, which will be carried in a high-performance Army aircraft. In this equipment, a relatively long physical antenna is utilized to produce a narrow fan-shaped beam perpendicular to the flight path of the aircraft and giving high azimuth resolution. High range resolution is obtained by the use of a short-duration transmitted pulse. This side-looking radiated beam employed in an aircraft provides the unique capability of rapidly obtaining a large-area radar photograph.

One other aspect of combat surveillance has to do with the location of weapons and the registration of friendly fire. In 1944, USASRDL became very much interested in applying radar to this problem, and a gradual evolution produced the present standard Army mortar locator, the AN/MPQ-4. The first attempt produced a single sector-scanning relatively large beam for intercepting the mortar shell at two points on its trajectory, on the up leg and the down leg, and permitting a

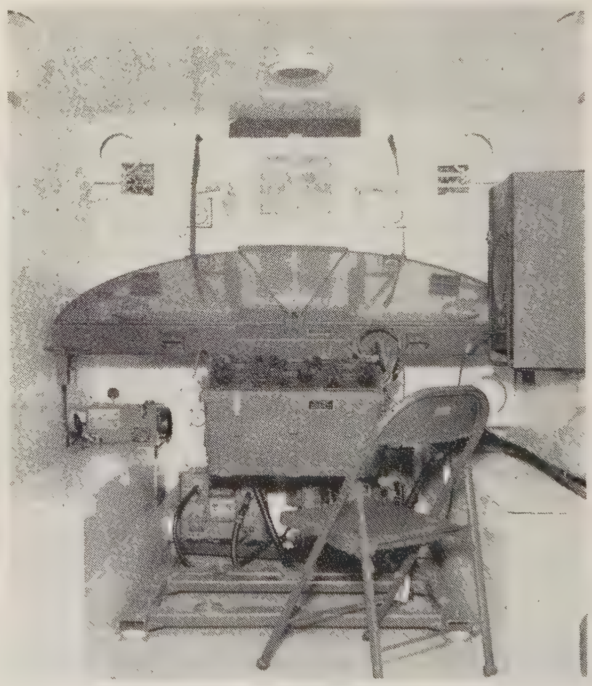

Fig. 8—Radar Set AN/TPS-25 (interior view of operating shelter).

rough extrapolation back to the mortar weapon. The next step in the evolution produced a tracking-type radar, to greatly improve the extrapolation accuracy for locating the weapon, but permitting only one location at a time until the tracking of one shell was completed. The next step produced the dual-beam intercept radar, which achieved a relatively wide azimuth scan for each beam by using a rapid scanning feed system (Foster Scanner), Fig. 9. Weapon location was obtained by extrapolating back from the pair of points ob-

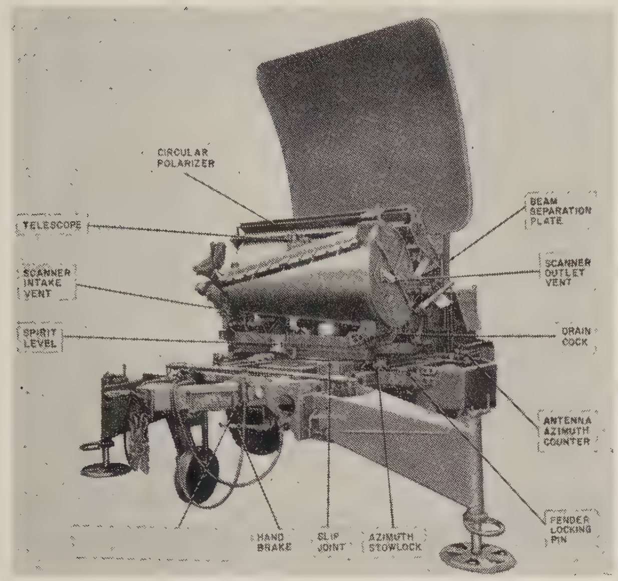

Fig. 9—Radar Set AN/MPQ-4.

tained on each mortar shell fired through the beams as shown in Fig. 10. This technique permitted many simultaneous weapon locations to be accomplished. The present production version of the AN/MPQ-4 was developed under a contract with the General Electric Company, Heavy Military Electronic Department, Syracuse, N. Y.

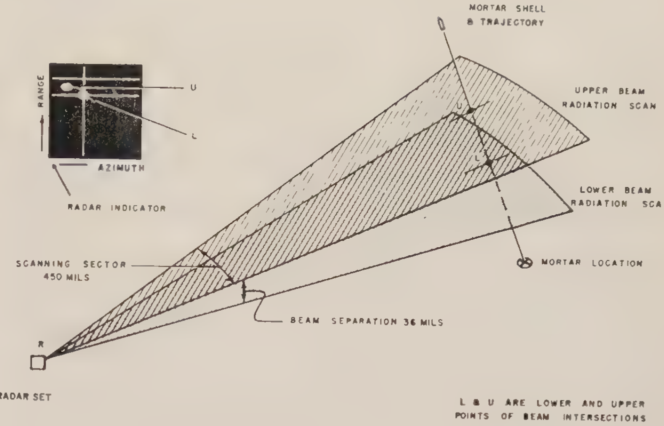

Fig. 10—Radar Set AN/MPQ-4 (geometrical view of beams in space).

The equipments discussed above represent some of the capabilities of radar as applied to surveillance and target location on the battlefield. Research and development is continuing within the U.S. Army Signal Research and Development Laboratory to further exploit the application of radar to additional combat surveillance functions including: mapping of terrain with resolution capability approaching optical quality; detection and tracking of nuclear burst clouds, with prediction of radioactive fallout; detailed analysis of storm clouds for weather control and prediction; and recognition of targets as well as their identification.

Lightweight Integrated Doppler Navigation System for Army Aircraft*

KENNETH K. KELLY†

Summary—**This paper presents some of the problems associated with the Signal Corps search for a suitable Doppler navigator for both lightweight fixed wing and rotary wing aircraft. The unique approaches discussed in detail are: The choice of a lightweight 3-axis stabilized antenna, position computation and display in cartesian coordinates for compatibility with Universal Transverse Mercator charts, a moving bug map display, a tape display of absolute and barometric altitude, and an integrated instrument system displaying navigation and flight information for all weather operation. These various components are combined to furnish the Army with a truly automatic self-contained navigation and flight instrument system.**

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Introduction

THE Integrated Doppler Navigator to be described represents the results of many years of planning and study conducted or sponsored by the Army. These studies were aimed toward the determination of the navigation and flight instrument system best suited to the specialized requirements of Army aviation.

As a result of these studies the development of an integrated primary navigation and flight instrument system was begun. The system consists of a lightweight Doppler radar to supply primary velocity information, an accurate magnetically slaved Gyrosyn® compass system, a vertical reference, and an integrated flight instru-

ment display. It will provide the Army pilot with all the essential information necessary to fly to any selected location accurately, safely, and reliably without any references external to the aircraft.

The study work on the Doppler radar indicated that a 30-pound system with 0.23 per cent velocity accuracy, 350-knot top speed, and 20,000-feet altitude could be designed to meet the requirements for both rotary and fixed wing Army aircraft.

In order to accomplish the objective, it was necessary to depart appreciably from 1955 Doppler radar designs. The proposed new features included a four-beam antenna stabilized in pitch, roll, and azimuth, elimination of analog processing circuits in position computation, and time sharing of the receiving sytem among the four antenna beams.

None of the navigation radars under development in 1955 could be built with a weight of less than 75 to 100 pounds, even when using weight reducing techniques. These radars used almost all possible combinations of analog or digital computation, various means of antenna stabilization, and CW or pulsed transmission. Therefore a completely new approach was needed.

Since the operation of the AN/APN-118 depends upon data derived from the Doppler effect, it may be well to digress for a moment to cover briefly the Doppler effect and its application to airborne radar.

If an electromagnetic wave is propagated between two points which are moving with respect to each other the transmitted and received frequencies differ by an amount called the Doppler shift. If the transmitter and receiver are fixed with respect to each other but are moving with respect to a fixed target, the Doppler shift is twice as great as for one way propagation. In this case, the frequency of the Doppler shift is, neglecting higher order terms,

$$F_d = \frac{2V}{\lambda} \cos \theta$$

where

F_d = Doppler frequency
V = velocity of the transmitter—receiver
λ = wavelength of radiation
θ = angle between the velocity vector and the direction of propagation.

Thus, if the wavelength (or frequency) of the radiation and the angle θ are known, the Doppler frequency can be used to obtain an exact measure of velocity.

If only one antenna beam is used, only the velocity component in the direction of that beam can be measured. Velocity components that are orthogonal to the antenna beam will not be detected. Thus in order to measure three components of ground speed such as north-south, east-west, and vertical, at least three antenna beams are required. The use of the fourth antenna beam does not in itself supply additional information, but often results in a simplification of over-all circuitry.

The use of multiple beams also relieves the problem of stabilization. If two antenna beams are fixed with respect to each other, one pointed forward and one aft, the Doppler shift in each antenna beam will be the negative of the other when the antenna platform is level and the aircraft is moving forward. If the antenna platform is tilted slightly, the decreased Doppler shift in one beam is compensated by an increased Doppler shift in the other. If velocity is measured by subtracting the two Doppler frequency shifts, the measured velocity is then relatively independent of small stabilization errors.

Description of AN/APN-118 Receiver Transmitter

The Doppler radar transmits four beams of microwave energy to the earth. It receives a portion of the reflected energy and extracts the Doppler shift of the signal to obtain three orthogonal components of the velocity vector of the aircraft. Since the radar is stabilized with respect to the earth axes, the velocity components are automatically derived in the north-south, east-west, and vertical directions. In the complete system the north-south and east-west components of aircraft velocity are fed to the memory circuit where wind information is computed and stored, *i.e.*, comparison of Doppler derived ground speed and drift angle with the aircraft true heading and true airspeed solves the wind triangle.

The peculiar and unique requirements for the AN/APN-118, together with the state of the art as it existed in 1955, dictated a design using the interrupted CW type of transmission. Since a pulse system has the receiver gated off for very close targets, range discrimination can be provided. This is useful in eliminating false Doppler shifts from propellor blades, rotors, and vibrating objects. At the same time the radar can operate at low altitudes because the large power received at such altitudes can be used to mask the fictitious shifts caused by moving objects. However, the pulse system requires more power than a continuous wave system because the received signal is not as well utilized as in CW systems.

In the interest of weight reduction, time sharing of several functions was necessary, thus relieving the need for four identical channels.

A single channel system was therefore selected using a single transmitter, antenna aperture and receiver, sequentially switched to derive Doppler velocities in the north, south, east and west directions.

The over-all system can be best visualized by observing the block diagram in Fig. 1. All systems except those stabilized in geographic coordinates require one or more resolvers to convert the data to the final coordinates. If the resolution is done digitally, several dozen tubes or transistors are required for each conversion. This raises weight and power requirements appreciably. The same is true if analog resolvers operating on 400-cps carriers are used. A precision data converter is required to

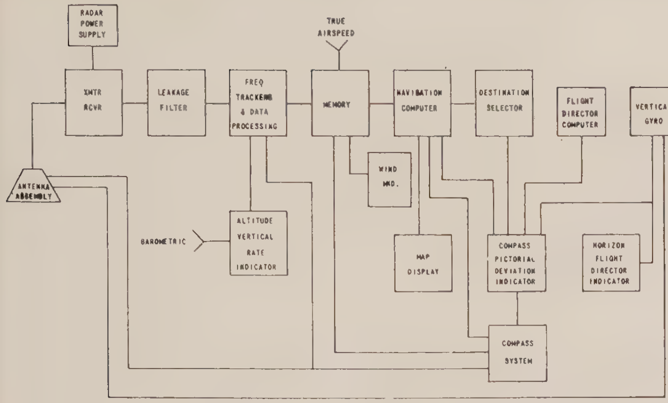

Fig. 1—AN/APN-118 functional block diagram.

change the Doppler frequency into a 400-cps voltage with an amplitude proportional to the original frequency. Either of these units can add from 10 to 30 pounds to the weight assuming the same system accuracy. The use of a four beam antenna, with the beams directed along the four principal compass points, 20 degrees off vertical for adequate sensitivity, permits a simplification of the data processing circuits.

Stabilization of the antenna in heading (yaw axis) is accomplished by using the aircraft compass for a north reference and rotating the four feed horns and their associated circuitry. The antenna can be completely turned about the heading axis; however limitations of 25 degrees have been applied to the pitch and roll axis which rotate the entire assembly. Limit switches are provided to indicate that the data are in error whenever the pitch and roll limits are exceeded. When these pitch and roll limits are exceeded, the system operates like a fixed antenna, except for the heading axis. A double gimbal system provides the rotating axis for pitch and roll. A 360° ring gear drive serves as the rotating mechanism for heading. Slip rings are used to feed the various voltages and control signals to the moving assembly.

If the angle between the forward and backward beams is held constant, a leveling error in the antenna platform causes an increase in the Doppler frequency of one beam and a decrease in the frequency of the beam that is back-to-back to it. This phenomenon, known as "Janus effect" (described in the Introduction) reduces the required stabilization accuracy for pitch and roll axes.

The analysis of heading error is the same as for the antenna misalignment error in the horizontal plane. The results show that the navigation error that occurs has a magnitude of 1.74 per cent of distance to the reference point per degree of heading error. This is the limiting error in the entire system. As an example, for a heading reference accuracy of 0.5 degree, an error of 0.87 per cent of distance traveled will result.

A significant step toward the achievement of this light-weight system was the development of a circular waveguide switch that will support two orthogonal modes without distortion. Therefore, only one duplexer and mixer are required instead of the four that were required previously.

This circular waveguide switch consists of a three-part waveguide junction with one input port and two output ports. A vane, centrally located at the junction, switches the input power to one of the two outputs. With the vane in one switch position, the input energy sees a 90 degree waveguide corner at the junction.

To summarize, the antenna is a four-horn antenna stabilized in pitch, roll, and yaw mounted on a 16-inch foam dielectric lens with an f/d ratio of 0.5.

Receiver

To extract the Doppler information at a useful frequency level it is necessary to heterodyne the Doppler signal from thousands of megacycles to hundreds of kilocycles. Establishing coherence between the transmitter oscillator and local oscillator compensates for any frequency change within the system. Coherence must be complete down to the reference input of the leakage filter.

The output of the Doppler radar receiver is a sine wave of varying amplitude and frequency which may be regarded as narrow band noise. The average frequency of this narrow spectrum of noise usually called the Doppler spectrum is equal to the Doppler shift to be measured. Since receiver noise which is always present will mask this average frequency, the effects of such receiver noise must be minimized. This is done by means of the frequency tracker.

Frequency Tracker

A frequency tracker is a device which converts the raw, noisy Doppler signal into a clean sine wave having the same average frequency. It is a variable frequency oscillator which is positioned at the center of the Doppler spectrum. By performing a limited amount of frequency averaging in the tracking-loop, it also reduces fluctuation error. However the amount of such averaging must be kept low because it results in dynamic error when the aircraft changes velocity. Furthermore the distance integrators act as low-pass filters and perform sufficient averaging.

Sequential switching to the four frequency trackers is obtained using an RF diode gate. There are four such gates, each associated with a particular frequency tracker.

The output of the leakage filter is amplified and switched sequentially through the gate to the frequency trackers. Operation of the gate circuit is synchronized with the RF switch and is controlled by a bistable transistor multivibrator.

Data Processing

The output of the frequency tracker oscillator is a sine wave having a frequency equal to a carrier frequency plus the Doppler shift. If the aircraft is traveling north, the signal from the north beam will increase in

frequency while that for the south beam will decrease. The algebraic difference of the two frequencies is proportional to the northern velocity and the integral of the difference is a measure of distance traveled north. The differencing and integration can be accomplished with either analog or digital techniques. In the case of AN/APN-118 digital counting can be easily accomplished by conventional techniques and with no loss in accuracy. Therefore, the computing circuits are digital. The outputs of the frequency trackers are four sine waves, one for each channel. Each sine wave is shaped to yield a pulse for each zero crossing.

This portion of the data circuit divides the input by 4096 and delivers an output pulse every 0.1 nautical mile. (In later models this will be changed so that each pulse represents 0.1 kilometer.) After deriving the horizontal Doppler components by mixing and summing the outputs of the frequency trackers the Doppler frequency variation is from zero to approximately 7050 cps for velocity variation of zero to 300 knots. To meet the required specification of one pulse per 0.1 nautical mile, it becomes necessary to divide by approximately 8460. This total division is accomplished by two cascaded networks. The first divides approximately by two, by time sharing an adjustable gate. A digital divider accomplishes the remainder of the division.

There are twelve identical binary stages comprising the divider. The output of the final transistor is a single-shot circuit. The time constant of the single shot has been chosen to develop a pulse of approximately 0.035-second width. A power transistor delivers the power pulse to the stepper motor which drives the present position counters.

Automatic Declination Computer

The automatic declination computer functions on the approximation that the declination varies linearly with distance. The automatic declination computer combines information on declination gradient and direction of maximum change with distance from the origin to obtain declination. Voltages proportional to distances traveled are fed into a resolver whose rotor is positioned to the angle of maximum gradient. The output of this resolver is proportional to the distance traveled parallel to the line of maximum gradient. This signal rotates the flux valve heading signal through an angle equal to declination to convert the magnetic heading detected by the flux valve into true heading.

Values for the gradient and direction of maximum change are obtained from available charts. The probable error of the declination values on these charts is about 0.5 degree. To improve the accuracy of the declination information, it has been mentioned previously that the value of declination at the starting point be accurately determined by means of the portable declinometer. This precise value of declination is used to correct the charts. The result is a probable error of about 0.1 degree per 100 miles. At 500 miles or over the accuracy is 0.5 degree, the probable error of the chart. The initial value read by the declinometer is accurate to 0.05 degree.

Without initial value correction, the error is about $\frac{7}{8}$ per cent for any distance traveled. Correcting the initial value greatly reduces the error. At 100 miles the error is reduced to $\frac{1}{8}$ per cent, while at 500 miles it is about $\frac{2}{5}$ per cent.

The direction in degrees of magnetic declination gradient, and the magnitude of declination gradient in degrees per mile, must be preset in the navigation computer controller (Fig. 2) to provide an initial datum point.

Instrumentation and Pilot Displays

The following functions must be manually adjusted or set in to the navigation computer controller console prior to flight:

- Magnitude of declination at the starting point.
- Declination gradient magnitude and direction.
- Latitude for coriolis and earth's rate compensations in the directional gyro.
- Present position.
- Radar silent, land, sea.
- Compass heading type (*i.e.*, grid north, true north, magnetic north, or free directional gyro).
- Standard parallel for map selection (this is to be deleted in production models).

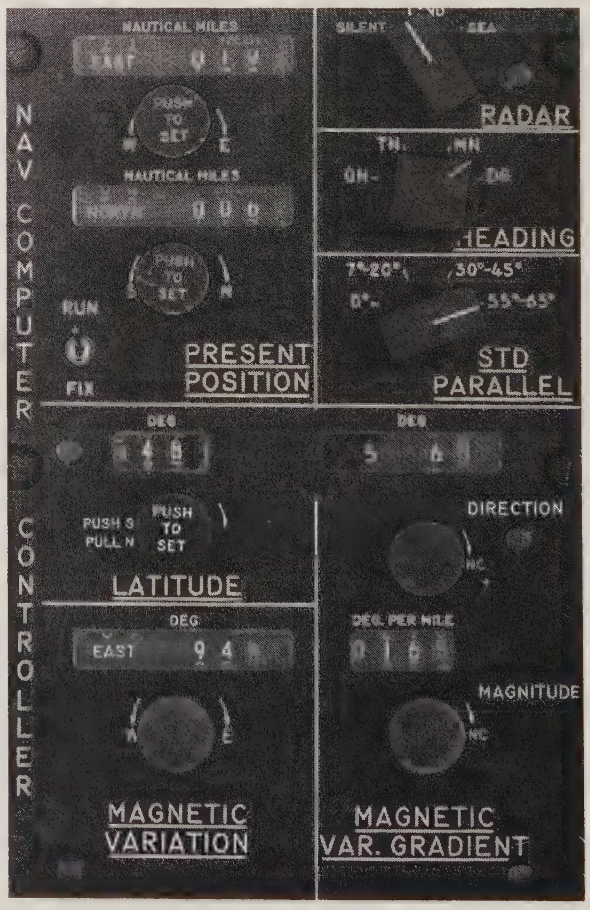

Fig. 2—Navigation computer controller console.

Destination Selector Console (Fig. 3)

In operation the coordinates of two destinations and the base are manually set into the counters on the destination selector console. For each counter (or coordinate) the "N" or "S" and "E" or "W" are appropriate selected by pushing or pulling the setting knob to the appropriate detented position. The detented positions allow the use of simple counters and reduce appreciably turning the knob to change settings (for example from E 180.6 nautical mile to W 120.0 nautical mile). After the destination coordinates have been set into the console, one destination is selected with the three-position toggle switch at the bottom of the panel. The selected destination is indicated by its respective indicator light and also by a mode flag in the compass pictorial deviation indicator.

Compass Pictorial Deviation Indicator (Fig. 4)

The compass pictorial deviation indicator is the primary navigation display of the AN/APN-118 system. This instrument indicates:

Aircraft heading on the moving card.
Ground track on the pointer.
Bearing-to-destination on the arrow-head over the moving card.
Distance-to-destination in nautical miles.
Selected radial to approach destination on the "railroad tracks."
Compass annunciator.
Target or base selected as destination.
Mode of radar operation.

The railroad tracks (two parallel white lines), which move perpendicularly to the four white dots, indicate to the pilot the necessary maneuver to approach destination on the selected radial. In an aircraft equiped with an autopilot the error signals generated by displacement of the railroad tracks can be used to automatically maintain a desired ground track. These steering signals are computed so that the approach to desired track is asymptotic.

Horizon Flight Director Indicator (Fig. 5)

The horizon flight director indicator performs the usual function of an artificial horizon with the following additional features.

1) It has both pitch and roll trim knobs for use in helicopters as well as fixed wing aircraft.
2) The cross-pointers can be used to display lateral and longitudinal velocities for hovering.
3) Pitch and roll command for fixed wing aircraft and cyclic pitch commands for rotary wing aircraft.
4) Collective pitch commands are provided to the helicopter pilot by means of a vertically moving index to the left of the attitude sphere.

This is a null type of flight director which requires the pilot to keep the pointers in a zero position in order to

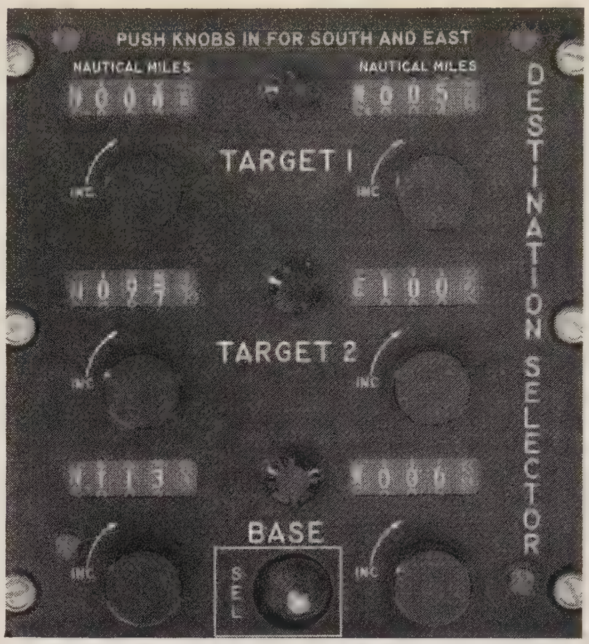

Fig. 3—Destination selector console.

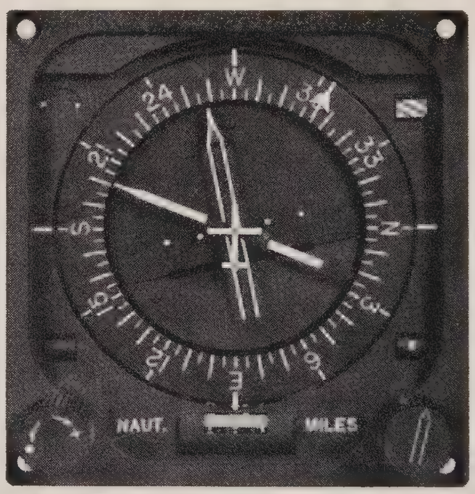

Fig. 4—Compass pictorial deviation indicator.

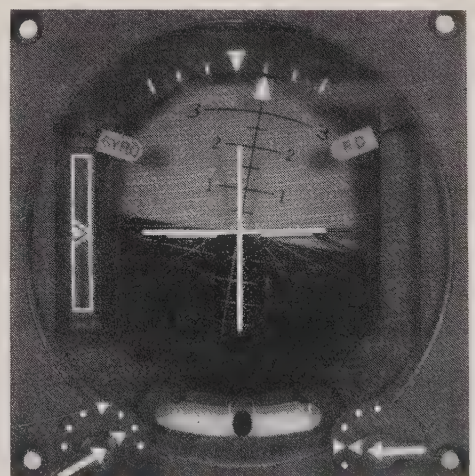

Fig. 5—Horizon flight director indicator.

stay on course at the proper altitude and in a rotary wing aircraft, at the proper airspeed. The cross pointers are biased out in view when not in use, depending upon the mode of operation selected on the flight plan selector.

Altitude-Vertical Rate Indicator (Fig. 6)

This indicator displays pressure altitude, absolute altitude, and vertical velocity in a logically integrated display. Barometric altitude and absolute altitude are presented on moving tapes. Vertical velocity is displayed by a moving pointer aginst a fixed scale. Deviation from level flight is indicated by a displacement of this pointer above or below the reference line.

This indicator includes a number of safety features. The vertical velocity scale operates in either of two modes. In one mode it receives information from the Doppler radar. However, if the radar signal becomes unreliable, vertical speed is automatically derived from the barometric-altitude servo. A mode flag has been provided on the face of the indicator to show the mode in which it is operating. Another feature provides minimum altitude warning. A visual indicator is provided to show the pilot that he is approaching his minimum desired altitude. This warning device may be used by the pilot over the entire range of the absolute altitude scale from 0 to 3000 feet. The portion of the tape below zero feet is marked with diagonal slashes to give a strong visual warning that the aircraft is approaching the ground.

The altitude hold circuit provides an electrical and visual indication for maintaining a desired altitude.The electrical signal may be used both by the flight director and an automatic pilot. This unit has been especially designed to be compatible with the Universal Automatic Flight Control System now being developed.

The altitude hold circuit has a memory of ± 500 feet. Over this range the instrument will remember the desired altitude. If this range is exceeded with the altitude hold feature engaged, the pointer and the electrical output potentiometer will disengage from the altitude servo and will remain in the extreme position. At the same time a reset warning flag will come into view. This warning flag will remind the pilot that the information is not reliable and that he should turn off the altitude hold circuit. Within a few seconds the altitude hold circuit may be engaged at the existing altitude.

Wind Indicator (Fig. 7)

A wind indicator has been included in the system because of its importance to the helicopter pilot in hovering, landing, and take off flight mode. During the landing manuever, the pilot desires to reduce his ground speed while maintaining a high airspeed. When a wind exists, this condition is accomplished by heading the aircraft into the wind. Thus, the pilot can fly within a given range of indicated airspeed at specific altitudes,

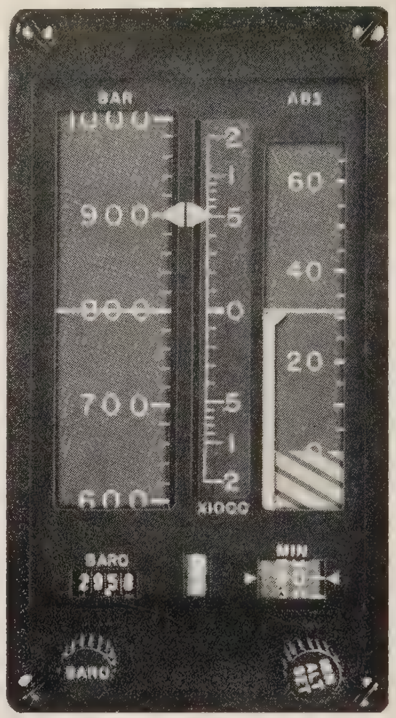

Fig. 6—Altitude-vertical rate indicator.

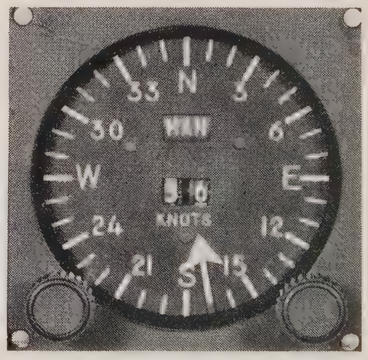

Fig. 7—Wind indicator.

avoiding the so-called "dead zone." In the case of power failure, the freedom of aircraft control and navigation during autorotation is facilitated when heading into the wind.

During a take-off or climb-out from the hovering mode, forward flight can be accomplished with a minimum settling effect if a sufficiently high airspeed can be attained. This can best be accomplished when heading into the wind.

A hovering helicopter will generally exhibit a tendency to turn into the wind. Therefore, it is desirable to hover into the wind in order to unburden the pilot to the degree involved in reducing frequency of pedal control responses.

Map Display (Fig. 8)

A novel feature of the system is a nine-inch-square map display which shows the pilot a visual picture of his aircraft's position and progress. Exact location of the

Fig. 8—Map display.

plane and its heading or direction of flight are electronically indicated by a moving pointer projected against aeronautical or grid maps of the area.

Conclusions

Through the incorporation of these advanced cockpit instrumentation concepts and new Doppler radar techniques not previously combined in a single light-weight self-contained system, precise navigation will be possible without dependency on ground based radio transmitters. This will give Army aviation the means for freedom of movement essential in meeting flight requirements for all-weather operation.

An experimental model of this new system (developed by the Sperry Gyroscope Company under a Signal Corps contract) capable of automatically guiding Army aviators to preselected destinations accurately and dependably is presently undergoing an engineering evaluation at USASRDL, Fort Monmouth, N. J. (See Fig. 9 for an artist's impression of the instrumentation installed in an L-23 aircraft.)

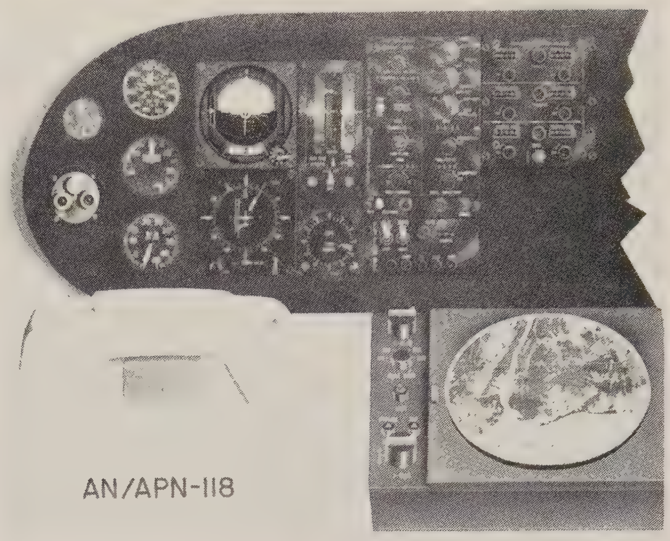

Fig. 9—Artist's impression of AN/APN-118 instrumentation installed in an Army L-23 aircraft.

Acknowledgment

The author gratefully acknowledges the assistance received from the Aeronautical Equipment Division of the Sperry Gyroscope Co. A great portion of the material included in this paper was derived from reports generated by Sperry under a Signal Corps contract and from meetings and visits held and made during the course of this development. The author is also indebted to L. Davis of the Avionics Division, USASRDL, whose supervision and creative suggestions contributed to this paper.

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Development of Meteorological Instrumentation at USASRDL*

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Summary—This article describes the development of electronic meteorological instrumentation at USASRDL from the early days of 1930, when practically no electronic equipment was employed for meteorological purposes, down to the present time. The discussion covers the development of radiosondes at high, VHF, and microwave frequencies, radio wind-finding equipment both manual and automatic, dropsondes to measure the temperature and humidity when dropped from an airplane and carried to earth on a parachute, weather radar equipment, sferics equipment for locating thunderstorms, rocketsondes, and other meteorological equipment. The history of various developments is presented as well as technical considerations which led to the engineering solutions to the various problems as they arose. The entire development program is related to progress in the field of meteorology and the usages of weather information which produced the urgency for developing the new types of electronic equipment.

MODERN meteorology and the ability to forecast weather have been made possible to a high degree by the instruments and systems developed by radio and electronic engineers. Prior to the age of electronic communications, man, for centuries, did possess the ability to forecast weather to some degree of success from visual observations of cloud and sky and ground measurements of pressure, wind, temperature, and relative humidity. But this type of weather forecasting from a single point of observation was severely limited, especially when visual facilities alone were employed for observation of the sky. The first big step in advancing the art of weather forecasting was made in the mid-nineteenth century when the meteorologist began to estimate the rate at which weather situations would move across the country. It was in this field that the electronic engineer first came to the aid of the meteorologist by providing communications to support the weather-forecasting system. In recent years radio engineering has come to the help of the single-station observer also by providing radar and sferics equipment to observe storms far beyond the range of the human eye.

The knowledge of weather phenomena was of course gained by the study of physics of the atmosphere and meteorology. For this academic purpose, weather patterns could be studied long after the observations were made and thus the observer could understand the nature of air-mass movements and modifications. But substantial progress in forecasting the weather in time to provide useful information to civil and military enterprises had to await the development of a rapid means of assembling weather data from large areas. This means was provided by the electric telegraph and the construction of communication networks covering large areas. The Government agency which specialized in communications over large land areas in 1870 was the natural one to create the first American weather service. That agency was the Signal Corps of the United States Army.

By 1935 great advances had been made in gaining a knowledge of weather phenomena, and efficient communications networks were in operation to support the weather services. However, at this time nearly all data were obtained from surface measurements, with the exception of those from visual observations of sky and clouds and wind data obtained by the tracking of small balloons with theodolites. With such apparatus the meteorologist could observe only a thin layer of the atmosphere near the ground, especially under cloudy conditions. The great need at this time was for better measurement of the atmosphere, not simply at the surface but also to great altitudes and under all conditions of visibility. In addition to the need for better measurements to support weather forecasting, information was needed for two entirely new requirements, both growing out of the experiences of World War I and the developments which followed.

The first of these requirements came from the development of long-range artillery, the emphasis on predicted fires for field artillery, and the development of anti-aircraft artillery. These artillery requirements called for an accurate knowledge of wind, temperature, and density to the maximum ordinate (45,000 feet) under any conditions of visibility. A second need was that of both military and civil aircraft for wind velocity at all levels for use in flight planning. All of these requirements pointed to the development of a radio means for sounding the atmosphere to great altitudes for obtaining temperature, humidity, wind speed, and wind direction, regardless of visibility.

One of the earliest steps in developing an instrument to measure the atmosphere by radio was undertaken by Col. W. R. Blair of the Signal Corps Laboratory, Fort Monmouth, N. J., in 1930. He developed a radiosonde (Fig. 1) which consisted of a simple radio transmitter to be carried aloft on a free balloon. This instrument operated at a frequency of three megacycles and was powered by small dry-cell batteries. Col. Blair had served in France during World War I as head of the Army's meteorological service and was well aware of the military requirements of both Artillery and Army Aviation. His initial objective was to measure only wind speed and direction by tracking the balloon-borne transmitter with an Adcock-type direction finder.

While the Adcock direction finder could be made to measure azimuth angles to a fair degree of accuracy (one degree) when located above smooth uniform ground and

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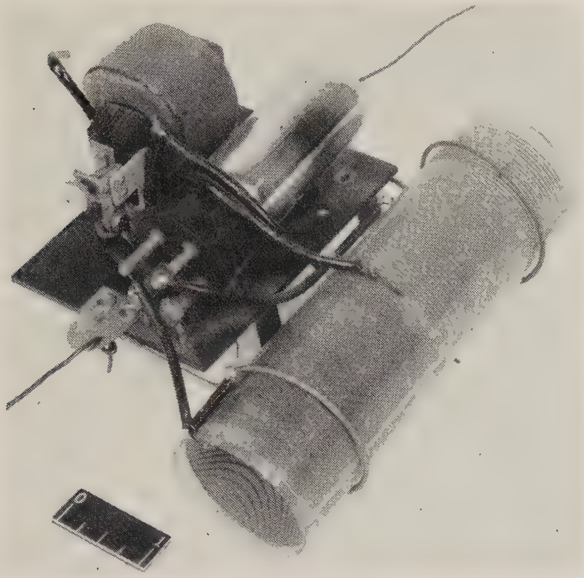

Fig. 1—3-Mc radiosonde (wind only) developed by Col. W. R. Blair in 1930.

receiving a radio signal along the horizontal, the problem became extremely difficult when the instrument was used to receive a signal from a balloon-borne transmitter at a high angle of elevation. There was no satisfactory way to measure the elevation angle which was also required for a complete determination of the balloon's position. Although considerable thought was given to this problem, there simply was no practical way to measure angles over rough terrain at the low frequency of three megacycles.

In January, 1939 a project was initiated at the Signal Corps Laboratory to develop a VHF vertical and horizontal radio direction finder for meteorological purposes. The radio art had now advanced to the stage where a 200-Mc radiosonde was feasible. At this frequency it was possible to build an array-type direction finder of practical size for field service, but such an array could obviously not be built at three megacycles. The array-type direction finder could be backed by a reflector screen and would be largely free of ground effects, in sharp contrast to the Adcock or loop direction finder. It therefore offered great promise for measuring both azimuth and elevation angles to a high degree of accuracy. This work was initiated under the guidance of Capt. J. D. O'Connell as project officer and R. I. Cole as supervising engineer. A. Pritchard developed the radiosonde, and the author developed the radio direction finder.

Just prior to this work an experimental VHF radio direction finder had been developed as a part of the first field radar set evolved by the Army. This finally became Radio Set SCR-268. The direction finder of this experimental radar consisted of one pair of antenna arrays for azimuth measurement and a second pair for elevation measurement. Each pair fed into its own double-input radio receiver. The two azimuth antenna arrays were physically displaced from each other by an angle of a few degrees to provide split pattern tracking in azimuth, and the pair of elevation antenna arrays were similarly displaced a few degrees in the elevation plane to produce split-pattern tracking in elevation.

Split-pattern tracking is the technique of employing an antenna system which provides two sharp directivity patterns or main lobes a few degrees displaced from each other so that the left side of one lobe intersects the right side of the other lobe at a sharp angle. This generally occurs at a magnitude of about three-quarters of the maximum value of each lobe. In tracking a source of radio energy, the antenna is moved until the radio signal arrives along the azimuth or elevation angle occupied by the intersection of these lobes. By a switching means, the receiver looks in succession at the signal received on each lobe, and the operator or servo mechanism moves the antenna array until the signal strength from both lobes is equal. This system provides precise direction finding.

This first meteorological direction finder, according to the instructions issued by Col. R. B. Colton, director of the laboratory, was to be developed in such manner as to obtain a split pattern from one array instead of two physically displaced arrays used in the radar equipment. No means for obtaining this result were known at the time. The first concept of the author of an antenna to provide this result was the employment of nonresonant transmission lines to connect the elements of the array in such a manner that delays in these transmission lines would provide a different pattern from one end of the array than from the other. An apparatus to demonstrate this effect was constructed and did produce the desired result (see Fig. 2). However, when a four-by-six azimuth antenna array was constructed with terminals at opposite ends, it was found possible to so adjust the impedances along the length of the array that the pattern obtained from one terminal was displaced the desired number of degrees from that obtained from the other terminal. A similar technique was used for the elevation antenna. These antennas are shown in Fig. 3.

The first successful employment of this direction finder in tracking a radiosonde carried on a balloon was made in the fall of 1939. During these tests the direction and angle of elevation of the radiosonde were measured to an accuracy of about $\frac{1}{4}$ degree, using a theodolite as standard. The flight lasted for about 15 minutes in a strong ground wind. This equipment demonstrated the practical usefulness of such a system in measuring the winds aloft under all conditions of visibility. During the following winter a development model of this equipment was constructed along lines considered satisfactory for tactical employment by the Artillery and Air Corps. This equipment is shown in Fig. 4. It consisted of an azimuth array six elements wide by four elements high and an elevation array six high by three wide. This equipment was mounted on a four-wheel trailer and so constructed that it could be disassembled for transporta-

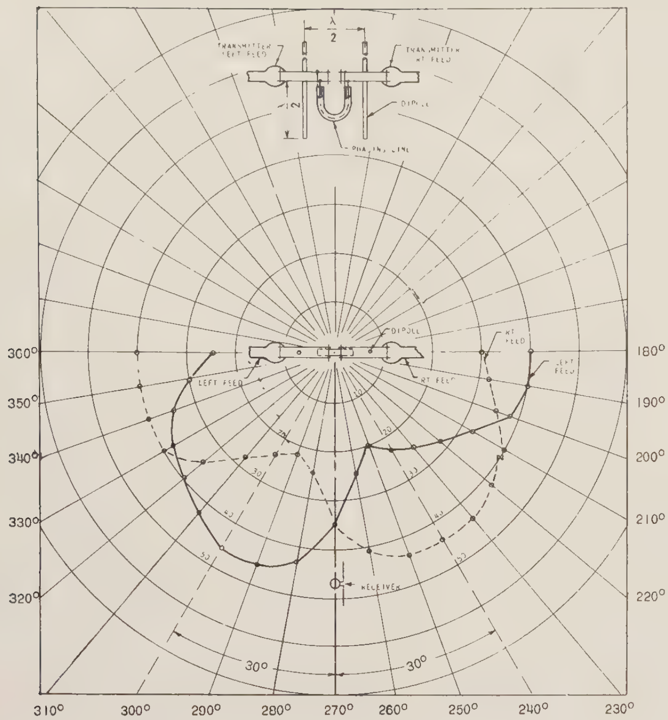

Fig. 2—Apparatus to obtain two displaced antenna patterns from one array by the use of a phasing line.

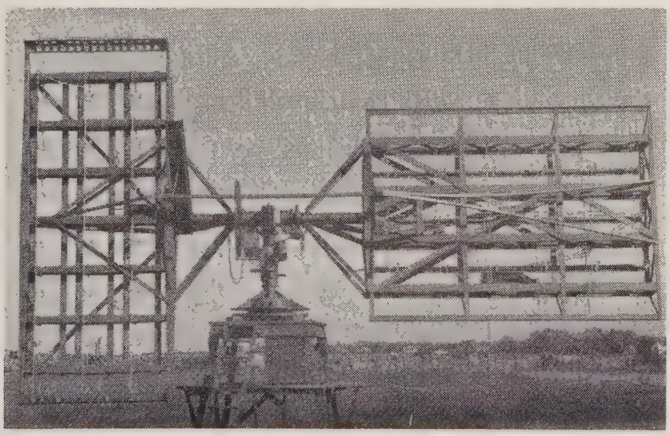

Fig. 3—200-Mc experimental meteorological radiosonde tracking equipment employed in 1939.

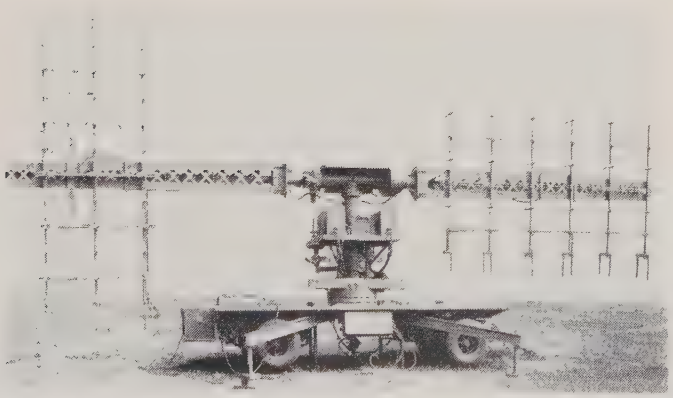

Fig. 4—Radio Set SCR-258, development model (200 Mc), 1940.

tion. This direction finder was known as Radio Set SCR-258. It was demonstrated to the Field Artillery at Fort Bragg, N. C., in the summer of 1940, and to the Army Air Corps and the Coast Artillery at Langley Feld, Va., during the same summer under the direction of Capt. O. C. Maier who has now assumed charge of the meteorological program. While this equipment measured winds to a reasonable degree of accuracy, it was considered too bulky for field use and therefore was never standardized.

In order to produce equipment to meet the mobility requirements of the military services, it was necessary to develop a system at a higher radio frequency. This would permit the same sharpness of antenna pattern to be obtained from an array of smaller physical dimensions. Development was undertaken at two frequencies: 400 and 1200 Mc. The fundamental difficulty of developing equipment at these higher frequencies was the problem of producing an inexpensive light-weight radio transmitter which could be operated from the low voltages available from a light-weight battery suitable for being carried aloft on a balloon. Progress in developing such a transmitter was chiefly dependent on advances in thermionic tubes and batteries. Initially the acorn tube type 955 was employed. Later, a subminiature tube type 5703 was adopted. At the same time the Battery Branch made major advances in the development of a light, efficient battery to provide the necessary power. Dr. A. Fishback was chiefly responsible for the development of a superior battery. The 400-Mc direction finder itself was developed by W. Todd and J. LeBedda, while the 1200-Mc work was done by R. Kirkman.

In the development of Radio Set SCR-258, the first step in reducing the antenna dimensions had been made by obtaining split-pattern tracking from one azimuth antenna instead of two mechanically displaced from each other, and a similar reduction in the elevation system. The 400-Mc direction finder (Radio Set SCR-658) was immediately reduced 50 per cent in height and width because of operating at twice the frequency of the older set. In addition, it was decided to still further reduce the size by combining the azimuth and elevation antenna arrays into a single array.

To obtain split patterns in both azimuth and elevation from a single array, it was decided to divide the array into four segments and use delay lines or nonresonant transmission lines to connect these together, following the basic principle illustrated in Fig. 2. The antenna consisted of six rows of six dipoles arranged to form a rectangular array of 36 elements. The nine elements in each corner of the array were connected together as resonant assemblies and these bays were then connected through nonresonant transmission lines to the center of the array. (The center dipole of each bay was actually removed to provide room for a symmetrical feed system.) The four transmission lines at the center of the array were connected through a motor-driven mechanical switch and delay system to the receiver. This switch consisted of a commutator which in succession grounded

matching transformers so arranged that at one time certain portions of the array were fed through a delay line of greater dimensions than a different portion of the array.

By proper combination of phasing lines, the antenna pattern was displaced in succession latterly and then vertically to produce a rotating antenna beam which provided split-pattern tracking in both azimuth and elevation. The output of the receiver was displayed on a cathode-ray tube in such a manner that a pair of vertical traces indicated the strength of the signals received on the two azimuth lobes and, on the same tube, a second pair of vertical traces compared the signal strengths received on the two elevation lobes. The operator turned the antenna in azimuth and elevation by cranks to match these pairs of traces in order to keep the antenna pointed at the balloon-borne transmitter. This equipment, shown in Fig. 5, was designed to be easily disassembled and packed for transportation on a one-ton, two-wheel trailer. The radiosonde is shown in Fig. 6.

In the fall of 1942 the experimental model of this equipment was tested and a radiosonde was successfully tracked to an accuracy of the order of 1/10 of a degree to a height of 40,000 feet. This equipment was then declared standard by the Army and the initial procurement was made for both the Artillery and the Air Force. The initial production of Radio Set SCR-658 started in January, 1943, and the equipment saw service in all theatres of operation by the end of World War II.

After the standardization of Radio Set SCR-658, there was an attitude of some of the users of this equipment that further advances in the state of the art were not necessary and certainly would not contribute to winning World War II. However, Col. McBride of the Army Field Forces took the long-range view that the work of the Army would not be finished when World War II had been won, and he strongly supported the effort of the USASRDL in continuing development at high frequencies. In the meantime, the work of R. Kirkman at 1200 Mc had been shifted to 1680 Mc and was now in direct charge of Dr. M. Kline. The limiting factor in development of this equipment was again the development of a transmitter which could operate on a balloon, with the severe limitations of low battery voltage and light weight.

Several efforts were made to develop a tube for this application, but success was finally attained by RCA which developed the 5794 tube entirely at its own expense and initiative. In the meantime, engineers working in this Laboratory under the guidance of Dr. Kline produced the first experimental model of the automatic direction finder shown in Fig. 7. This direction finder

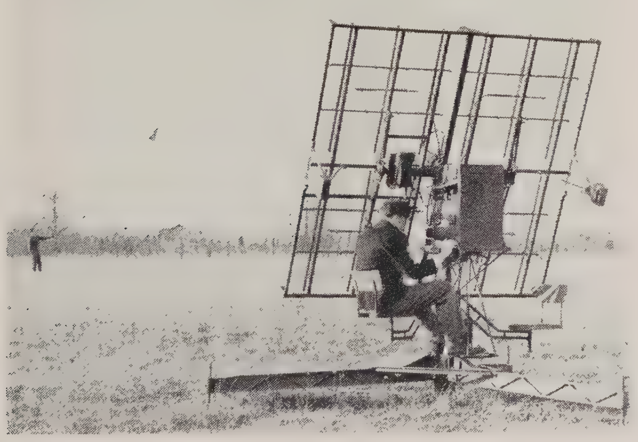

Fig. 5—400-Mc meteorological direction finder, erected for tracking a radiosonde (Radio Set SCR-658).

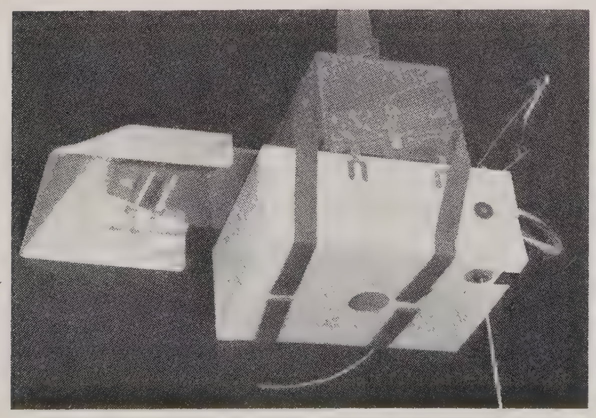

Fig. 6—400-Mc radiosonde.

Fig. 7—Experimental model of 1680-Mc automatic radio meteorological direction finder constructed at USASRDL in the spring of 1945 (forerunner of Rawin Set AN/GMD-1).

(Rawin Set AN/GMD-1) employed a parabolic antenna, following the practice set in the development of radar equipment. However, it utilized a special type of scanning system in order to provide a vertically polarized receiving antenna. This was necessary to receive the signal transmitted by the radiosonde which employed a vertical dipole. Actually, the polarization received from a balloon-borne transmitter is far from vertically polarized under many instances as the transmitter swings at the end of its cord suspended from the balloon. However, when high winds prevail and the balloon is carried far away from the tracking site, maximum sensitivity is required to receive the radiosonde signal. Fortunately, at this critical time, the balloon is usually at a low elevation angle and the signal is then vertically polarized to a reasonably high degree.

The antenna developed by Dr. Kline employed a dipole at the approximate focus of an eccentric hemisphere which was located just inside the focus of the parabola. The mechanical rotation of this hemisphere produced a rotation of the antenna beam in a similar manner to the techniques now generally employed in radar tracking equipment, but preserved vertical polarization of the system, at least when the antenna was aimed at the horizon.

While Radio Set SCR-658 was manually operated, Rawin Set AN/GMD-1 was made completely automatic. In 1945 there was real doubt as to whether to abandon manual operation and accept the greater complications of completely automatic equipment. This is a characteristic problem which arises in the development of military equipment. The advantage of the automatic equipment in saving manpower may be completely offset by the extra manpower required for maintenance. However, in this case the development of the automatic direction finder did more than relieve the soldier in the field of the routine duty of keeping the antenna array on bearing. It demonstrated the fact that a machine can perform a routine operation of this type to greater precision than a man, because of greater attention to a routine requirement. Continuous training was necessary to convince the operator that he had to keep the traces of Radio Set SCR-658 precisely matched in order to obtain good results. (He was satisfied with an approximate match.) The machine performed this function faithfully, thereby increasing the accuracy of the equipment substantially.

Rawin Set AN/GMD-1 (Figs. 8 and 9) as finally developed operated at a frequency of 1660 to 1700 Mc. The parabolic antenna was seven feet in diameter or 12 wavelengths as contrasted to the seven-by-seven-foot array employed in Rawin Set SCR-658 which was approximately three wavelengths square. This increased dimension of the array measured in wavelengths naturally contributed greatly to the accuracy of the direction finder because of sharper antenna beams. A further increase in accuracy was provided by the fact that the sharper pattern eliminated ground reflections to a far greater degree than the relatively broad-beam antenna of Rawin Set SCR-658. Rawin Set AN/GMD-1, as finally tested, was capable of tracking a balloon in azimuth and elevation to an accuracy of 1/20 of a degree down to an elevation angle of six degrees. At this elevation, ground effects again appeared and produced an appreciable error of a fraction of a degree. Rawin Set AN/GMD-1 was standardized by the Air Force and the Army in 1949 and has now become the basic equipment employed by all military services for sounding of the atmosphere to an altitude of the order of 100,000 feet. A similar equipment is now the basic sounding equipment of the Weather Bureau.

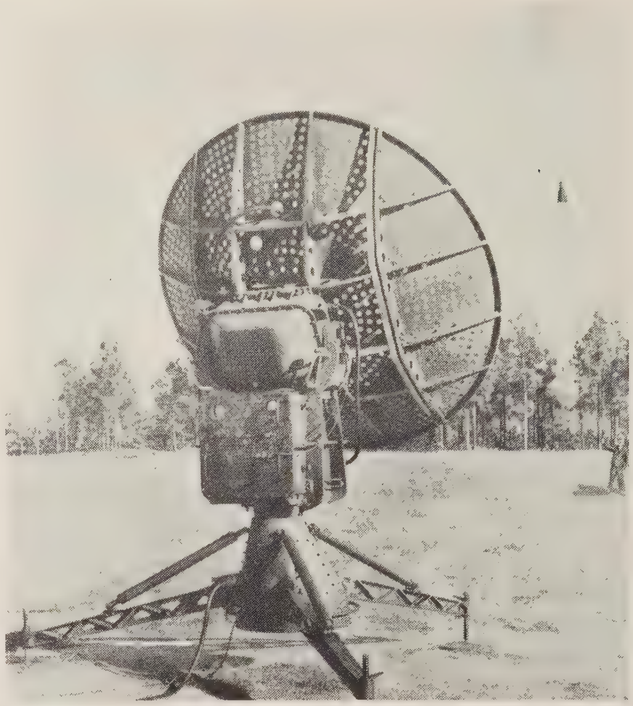

Fig. 8—Service-test model of Rawin Set AN/GMD-1, 1680-Mc.

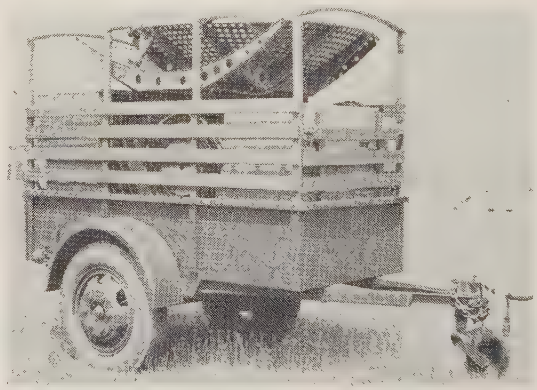

Fig. 9—Rawin Set AN/GMD-1 packed for transportation.

Rawin Set AN/GMD-1 had hardly been developed when the laboratory engineers conceived of the advisability of developing a still more accurate equipment for determining winds aloft. Rawin Set AN/GMD-1 was a radio theodolite. It measured angles of elevation and azimuth and used the pressure switch in the radiosonde

to determine altitude and thus fix the position of the balloon. It was very fine for determining winds aloft when the balloon rose at such a rate as to present a reasonably high angle of elevation to the ground tracking equipment. However, when high winds existed in the atmosphere—and winds of 100 miles an hour are often experienced at an altitude of 20,000 feet—the balloon was carried away from the launching site so rapidly that elevation angles were decreased to low values of the order of eight degrees. Under such circumstances a radio theodolite like a visual theodolite is at a great disadvantage in measuring wind velocities. The geometry of the problem of determining the slant range to the balloon under such circumstances is extremely difficult because small errors in elevation angles produce large errors in slant range and, in turn, excessively large errors in the computed wind velocities.

One means of overcoming this difficulty is to use a balloon which will rise more rapidly than a standard balloon. The angle of elevation of the balloon at any time during its flight is determined by the relative values of the mean wind velocity during the entire flight and the rate of rise of the balloon. The angle of elevation of the balloon at any time during high winds is nearly directly proportional to the rate of rise. If the rate of rise can be doubled, the elevation angle can be doubled; and since the error in wind velocity measured with a radio theodolite varies with the cosecant squared of the angle of elevation, a fast-rising balloon can decrease the error by a large factor without even considering the reduction in error gained by eliminating ground effects. By designing a balloon with a streamlined shape it was found possible to increase the rate of rise of the balloon from 900 to 1700 feet per minute while only increasing the amount of hydrogen from 100 to 170 cubic feet. In previous experiences with a stiff spherical balloon, 300 cubic feet of hydrogen were required to attain an ascension rate of 1600 feet a minute. This streamlined balloon provided one practical solution to the problem.

Another way to overcome this difficulty would be to make direct measurements of slant range as with radar. Radar had not been applied to the meteorological problem at an earlier date because of the economics of systems design. The meteorologist required not only the winds aloft, but also the temperature and humidity structure. No way was seen to measure temperature and humidity except by sending physical sensing elements aloft on a balloon and telemetering the data down to earth. The same transmitter used to telemeter these data could be employed most economically as the target of the direction finder on the ground in order to measure wind velocity. This combination also provided far greater range for following the balloon than was obtainable with radar equipment of practical size for tactical use during the 1940's. For these reasons the wind-finding problem had been solved by employment of a radio theodolite on the ground and a radio transmitter on the balloon, instead of employment of a radar set on the ground with a reflector on the balloon.

It should be mentioned that while radar equipment for wind-finding purposes was investigated, and while tactical radar equipments were employed to measure winds for the military services during World War II, these equipments were limited by the maximum range to which they could determine meteorological parameters and by the fact that they did not provide the temperature and humidity data. On several occasions investigations were made of an inexpensive transmitter for telemetering these data only, combined with a corner reflector and radar to measure winds, but the economics of the problem never justified the development of such a system.

In 1947 a project was initiated at USASRDL to incorporate the most economical type of range-measuring technique into the radiosonde system to provide a research tool. These studies indicated that the most economical design would be one in which a VHF transmitter was used on the ground to send a signal to the radiosonde on the balloon. The radiosonde would receive this signal and transmit the intelligence back to the ground via the normal radiosonde transmitter. This circuit would be used to measure range without otherwise interfering with the measurement of angles and the transmission of temperature and humidity data as performed in the standard Rawin set. This equipment was known as Rawin Set AN/GMD-2 and was developed with Kirkman, Todd, and LeBedda as the principal engineers.

This equipment employed a 20-watt, 400-Mc transmitter on the ground, modulated by an 82-kc sine wave signal. This range signal was received by a special radiosonde on the balloon, and the 82-kc signal was impressed upon the 1680-Mc carrier of the radiosonde. The range signal extracted from the 1680-Mc carrier at the ground station was compared in phase with the range signal being transmitted at that instant from the ground equipment. The difference in phase was used to measure the slant range to the balloon.

The 82-kc range signal has a two-way wavelength of about 2000 yards. This range-measuring system could therefore measure slant range of the balloon accurately to a fraction of the 82-kc wavelength, but could not tell how many wavelengths existed between the ground equipment and the balloon. However, the design of a practical system for sounding the atmosphere presented no problem because the balloon could be tracked continuously from the time of release from the ground station, and the range-measuring system would therefore at all times give a true measurement. Since a large number of radio theodolites, Rawin Set AN/GMD-1, had already been produced and were in use by the Army, Air Force, and Navy, this range-measuring system was eventually designed as an attachment to this standardized equipment. It was found possible to attach the 400-Mc radio transmitter, the phase-measuring system, and the special antenna to the existing equipment

with a minimum amount of modification required in the field. This equipment, Rawin Set AN/GMD-2, is shown in Fig. 10. The radiosonde is shown in Figs. 11 and 12. This system has recently been standardized by the U. S. Air Force, and a number of these equipments have been procured for the U. S. Navy.

With the development of Rawin Sets AN/GMD-1 and AN/GMD-2 and the associated radiosondes and balloons, equipment was available for sounding the atmosphere to 100,000 feet at a reasonably high degree of accuracy to meet the requirements of artillery, aircraft operation, general weather forecasting, and a new military need—that of making fallout predictions of radioactive dust resulting from atomic explosions. The meteorologist was no longer restricted to looking at a thin layer of the atmosphere. He could now see 99 per cent of the atmosphere with his rawinsonde, for only 1.0 per cent of the mass of the atmosphere exists above 100,000 feet. This coverage was quite adequate for meeting the current needs of operational users. But even this performance was not enough to support the extensive research and development requirements of all the Technical Services of the Department of the Army and the other military services. Temperatures, densities, and winds were now desired to 200,000 and 300,000 feet. This information was needed especially for the design of big rockets, but it was also required for fundamental considerations related to supersonic aircraft, space vehicles, and general knowledge of the upper atmosphere. Even for soundings up to 100,000 feet, better performance was required. Pressure and temperature measurements were needed to higher accuracy in the region of 70,000 to 100,000 feet. There were requirements to measure ozone, atmospheric electricity, drop size, and turbulence. There was also the need to process the large amount of data obtained by automatic computers instead of by manual methods heretofore employed.

Many of these problems have been met to a reasonable degree by activities of the USASRDL, but a complete coverage of these activities would exceed the space appropriate for this presentation. It must suffice at this point to illustrate these additional contributions of radio engineering to the field of meteorology.

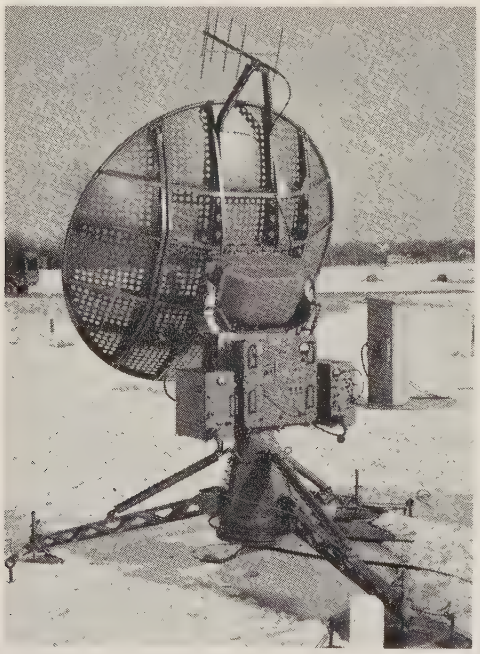

Fig. 10—Range-measuring radiosonde tracking set (Rawin Set AN/GMD-2) (attachments to Rawin Set AN/GMD-1).

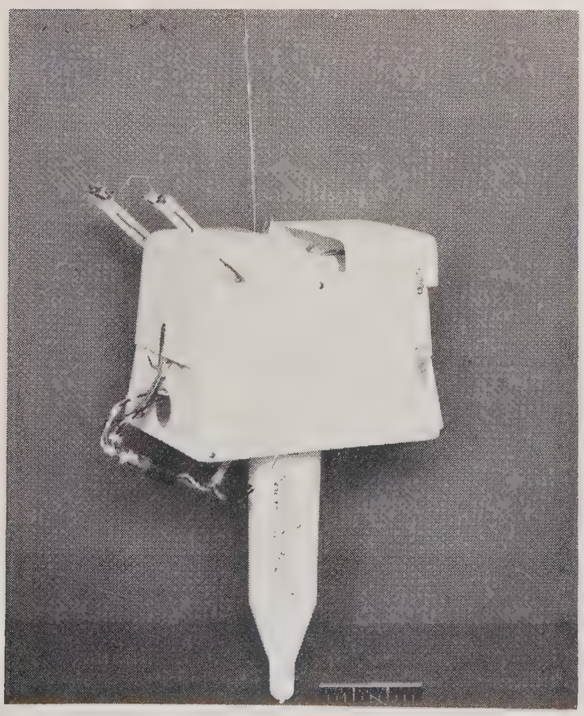

Fig. 11—Range-measuring radiosonde AN/AMQ-9, development model.

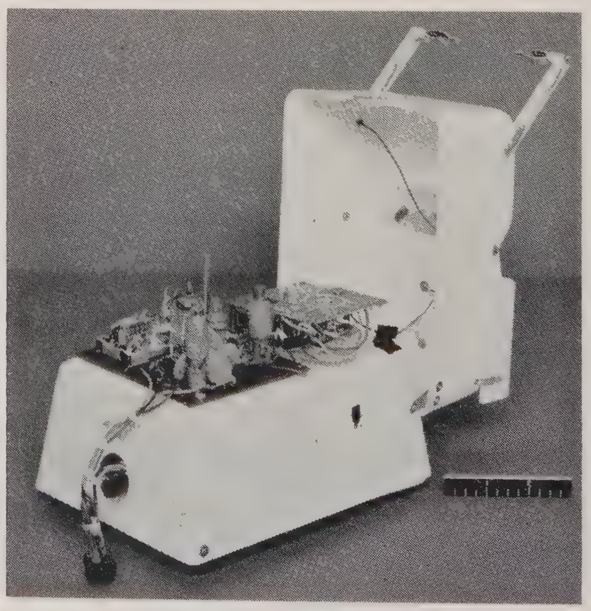

Fig. 12—Radiosonde AN/AMQ-9, showing 400-Mc receiver and clock switch.

Fig. 13 is a Loki rocket loaded with chaff cut to resonance at a frequency of 3000 Mc. This rocket is fired to an altitude of 200,000 feet where the chaff is discharged. As this chaff falls slowly to earth it is tracked by radar equipment on the ground to measure wind velocities. This system, developed by Dr. H. aufm Kampe, M. Wetzel, and A. Ivins, provides reasonably good data in the region of 200,000 to 100,000 feet altitude. One fundamental difficulty when using an automatic tracking radar is the fact that as the chaff falls it disperses. Eventually two or more centers of principal echo return may develop and confuse the radar. Finally, dispersion is sufficiently great to cause termination of tracking. This generally occurs after about 100,000 feet of fall.

In order to measure temperature and density as well as winds above 100,000 feet, the development of a rocketsonde was undertaken by Ivins and Coppola. The equipment consisted of a miniaturized radiosonde to be carried aloft on a rocket to 200,000 feet and there discharged to float to earth on a parachute. This radiosonde was designed to operate with Rawin Set AN/GMD-2 as a range-measuring, wind-finding set combined with a temperature- and pressure-telemetering radiosonde. High-voltage power for the transmitter was developed by a transistor oscillator operating off the low-voltage battery supply. This permitted the use of a six-volt battery, with a saving in weight and size over the use of a high-voltage battery as used in the standard radiosonde and greatly improved reliability. On the negative side, the cost of this power source was considerably more than a battery supply and would be objectionable for the general balloon-borne system. Fig. 14 shows the complete assembly of this rocketsonde on the Arcas rocket, and Fig. 15 is a close-up of the rocketsonde.

Both the rocket chaff system and the rocketsonde employ a physical element or elements to sense the atmospheric conditions. These elements must assume a condition of movement or temperature representative of the air molecules before their condition can be measured by the sounding system and the characteristics of the atmosphere thereby inferred. Such a system works well in the lower atmosphere where the air is sufficiently dense to bring the probing element to a condition of equilibrium in a short time. But the density in the atmosphere decreases by a factor of approximately 10 for each 50,000-foot increase in altitude. Therefore, at 200,000 feet the density is about 1/10,000 of that occurring at the earth's surface. Under such conditions a parachute will fall very rapidly and it will fall a great distance before it acquires the speed of the wind. Likewise, a temperature element must be exposed to the thin air for a long time before it acquires the temperature of the air. Furthermore, since this element is continuously radiating heat to outer space and receiving radiation from the sun (in the daytime), it may never come very close to the true air temperature. The limitations of such sensing probes are serious problems at very high altitudes. One system for atmospheric sounding overcomes this problem entirely by using the air molecules themselves as the sensing elements. This principle is used in the rocket-grenade system.

In the early part of 1947 USASRDL entered upon a research program for determining the characteristics of the atmosphere up to approximately 300,000 feet. This

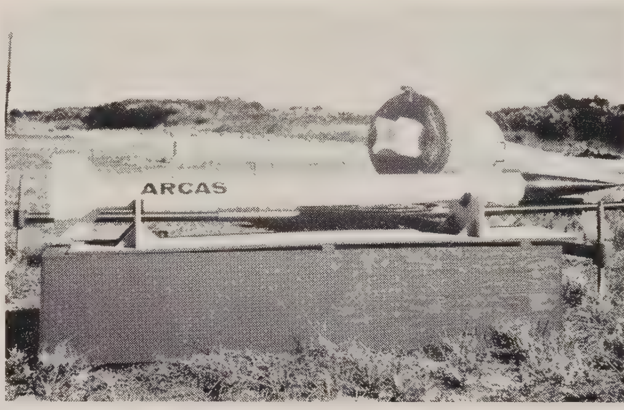

Fig. 14—Rocketsonde for soundings up to 200,000 feet (complete assembly).

Fig. 15—Rocketsonde, details of construction.

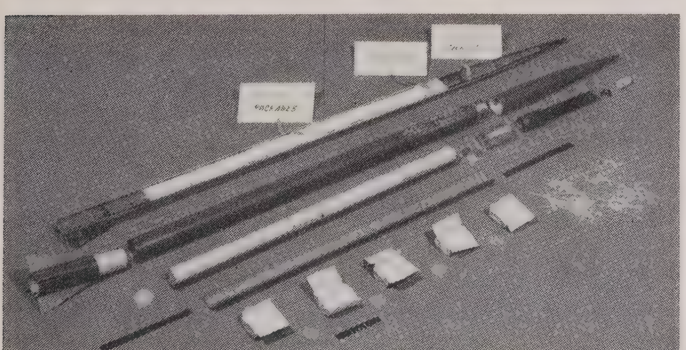

Fig. 13—Loki rocket loaded with chaff for wind measurements between 100,000 and 200,000 feet.

program was directed by Dr. M. Ference, then Chief of the Meteorological Branch. In this technique a rocket of the order of 8 inches in diameter and 15 feet in length is fired to an altitude of approximately 300,000 feet. Beginning at 100,000 feet, grenades are ejected every 15,000 feet and exploded. The precise position and time of each explosion are observed by suitable cameras on the ground and telemetering devices. Subsequently, the time and direction of arrival of the sound waves are measured at the ground with suitable microphone arrays. From these data it is possible to compute the speed of sound in each layer of the atmosphere between grenade bursts and thus derive the air temperature. By considering the direction of arrival of the sound waves on the ground and the point of grenade burst, it is also possible to compute the deflection of the sound waves by the winds aloft and thus determine the winds in each layer between grenade bursts. Space does not permit a description of the electronic equipment employed in this system, but a number of radio and electronic techniques are apparent. This same system with fundamental refinements in the tracking means was employed by W. Stroud, Dr. Nordberg, Capt. Fincher, and Capt. Bandeen during the IGY to make a series of soundings between 100,000 and 250,000 feet altitude at Fort Churchill, Can., and on the Island of Guam. Obviously, the rocket-grenade sounding system is costly and complex, but it does possess the merit of being able to measure the extremely thin atmosphere at very high altitudes as few means are able to do.

Besides temperature, humidity, and winds which have been discussed up to this point, a number of other elements came under investigation for research purposes. Fig. 16 is an electric radiosonde used to measure either conductivity of the atmosphere, air-earth current, or potential gradient, depending on which system of antenna and impedances is attached to the terminals. This instrument is an adaptation of the standard radiosonde, and the information telemetered to earth is received on Rawin Set AN/GMD-1. This equipment was developed by a contractor following the design criteria laid down by Dr. H. Kasemir to meet his requirements for research in the field of atmospheric electricity. Special instruments have also been made available for the measurement of ozone, turbulence, and wind shear in the atmosphere. However, these will not be discussed in detail because they do not present problems of particular interest to the electronics engineer.

Previous reference has been made to single-station techniques for weather forecasting as contrasted to the grid system of large area observation and map analysis of the weather. Consideration will now be given to the problem of single-station weather-forecasting instrumentation. For centuries man based his forecasts of the weather chiefly on electromagnetic observations, but at the time they were known as visual observations. After the development of electronic communications and airmass analysis, weather prediction was only slightly dependent on direct observations by the forecaster. However, during World War II, the meteorologist was given two new tools which permitted him to once more place considerable dependence on direct electromagnetic observation. These tools are weather radar and sferics.

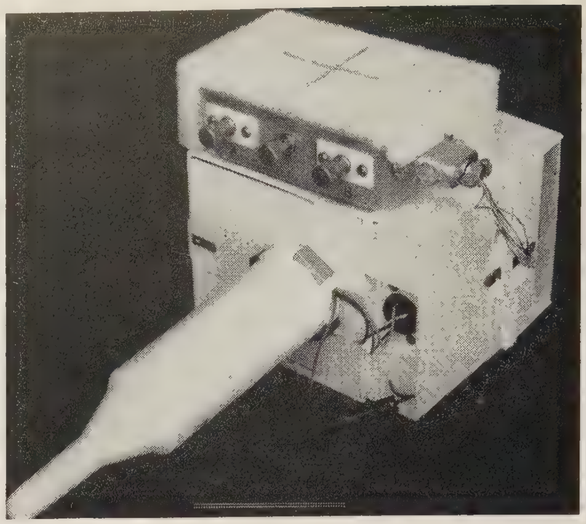

Fig. 16—Electric radiosonde.

Radar development itself started in the late 1930's as an attempt to avoid the restrictions of clouds and water droplets which so greatly hindered the observation of enemy aircraft by visible means. This was done by dropping far down into the electromagnetic frequency range where radio signals are largely free from interference by clouds and precipitation particles. However, as the radar designer subsequently pushed his frequencies higher and higher to obtain sharper antenna patterns and better reflections from small objects, he eventually ran into trouble by getting echoes from meteorological phenomena. Trouble came first from raindrops. Then as the frequency went still higher, trouble came from discontinuities in the atmosphere and finally from water vapor itself in the gaseous state. But there is a basic principle in all human endeavor that any adversity or obstacle of unusual dimensions is likely to possess great possibilities of exploitation to those that see the opportunity. Thus, trouble for the radar designer became an area of great opportunity for the meteorologist.

A group of engineers and scientists in USASRDL including Dr. D. Swingle and W. Gould, H. Brooks, R. Wexler, and J. Weinstein set out in 1946 to exploit this opportunity to the maximum. By internal development and later by contract, Weather Radar Set AN/CPS-9 was developed, and standardized in 1950 (see Fig. 17). With this equipment it became possible to observe rainstorms out to a distance of 200 miles and to follow the movement of frontal storms hour by hour as they advanced on an airport or other important installation. Not only does this permit detailed forecasts with far greater accuracy in the intermediate scale of time and distance than by previous means, it also permits the

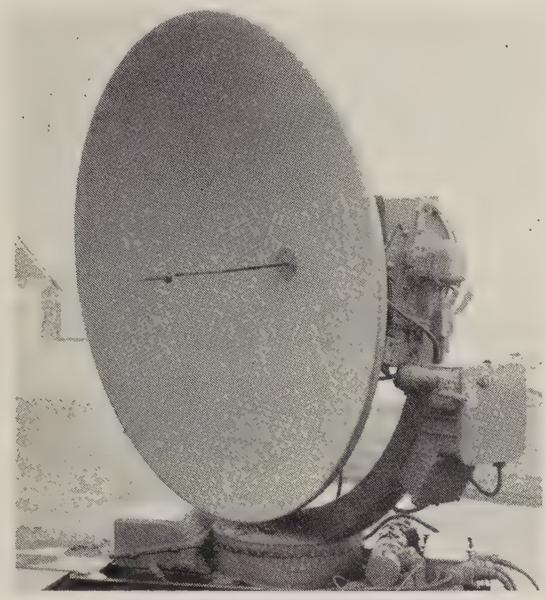

Fig. 17—Experimental model of Weather Radar Set AN/CPS-9.

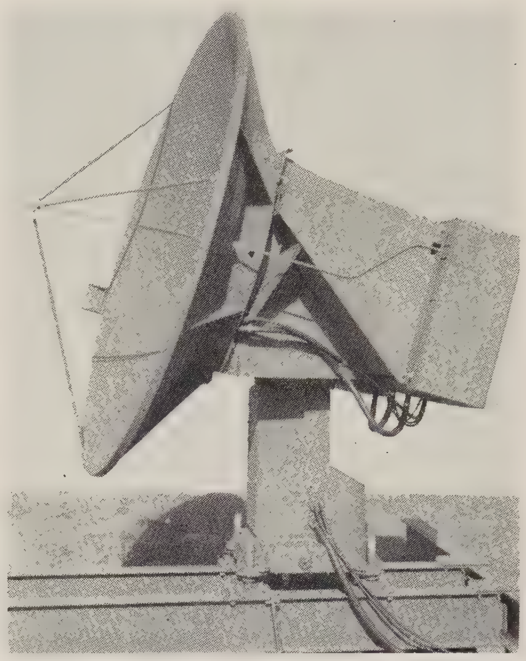

Fig. 18—Antenna of cloud base and top indicator—1.25 cm.

theoretical meteorologist to see a complete picture of the cell structure of storms over a large area and thus obtain an understanding of the weather never before available.

Radar Set AN/CPS-9 employs a 250-kw transmitter operating at a frequency of 10,000 Mc (3 cm). A relatively long pulse length is employed to obtain maximum sensitivity. Several types of scan and data presentation are provided, but the most used technique is the P.P.I. presentation on a 15-inch long persistence cathode-ray tube.

Radar was further exploited by this same group which undertook at still higher frequencies to observe clouds as well as raindrops. A weather radar set was developed at 1.25 cm wavelength to see clouds overhead. An experimental model of the antenna of this set is shown in Fig. 18. This set became known as the cloud-top-and-bottom indicator because it could see the small water droplets which made up the several layers of clouds above the ground station. This equipment was called Radar Set AN/TPQ-6.

"Sferics" is a term used by the meteorologist to designate electromagnetic disturbances occurring in the atmosphere. Sferics are presumed to consist exclusively of radio waves resulting from lightning discharges. A direction finder for taking bearings on such disturbances was developed by Watson Watt in the 1930's, and extensive research was conducted by the University of Florida, Gainesville, in that same decade in an attempt to track hurricanes by locating lightning sources. Little came of this work because a hurricane is not productive of much lightning. During World War II the British installed a network of static direction finders in England. By using telephone lines for coordination, the operators manually recorded bearings on lightning simultaneously from a series of stations. The areas of lightning activity plotted from these data were found to be of extreme value to Air Force commanders sending bombing missions into central Europe. Not only were the storm areas of interest because they represented bad weather to be avoided, but lightning was also useful in giving an indication of frontal movements of the air masses which were the basis of weather forecasting. Radio direction-finding equipment operating at 10 kc was developed at USASRDL during the last part of World War II to provide the U. S. Air Force with the means of establishing sferics systems similar to the British.

During 1954, L. Pick and K. Steelman undertook to develop an automatic system for locating sferics on a map presentation. Ten-kilocycle automatic radio direction finders were to be employed on a triangular base 500 to 800 miles on a side as in the manual system. However, instead of manually plotting the bearings, these were to be taken and relayed automatically to a central station where they would be presented on a cathode-ray tube with completely automatic computation of data. Consideration had previously been given to developing a time-difference system in which the time of arrival of the lightning radiations at several points of observation was relayed to a central point and the source of the lightning was then computed from these times of arrival. This was the old sound-ranging technique originated in World War I for locating artillery, but now using radio waves in place of sound waves. It also was Loran in reverse. However, such a system lacks flexibility for military use and it is also hard to obtain radio frequency allocations for the relay links. Clearly, the relay links must introduce only a known amount of phase delay, and this is difficult with sky-wave transmission. Furthermore, the relay links must have broad bandwidths in order not to introduce too much phase distortion so as to faithfully

relay the time of arrival of the lightning-generated pulse. A system based on radio bearings obtained with direction finders could use telephone or radio-telephone circuits of standard design for the relay links. Such a system seemed far more practical for a general-purpose sferics system for the military services than a time-difference system.

In the automatic sferics locating system as designed and constructed by Pick and Steelman, a bearing is presented on a cathode-ray tube in the same manner as the standard Watson Watt instantaneous direction finder. The bearing is a radial line along the azimuth of the lightning source. A pick-up device scans the circumference of this cathode-ray tube and measures the time between intersection of zero azimuth index and the bearing radius. An orthicon is actually used in place of a cathode-ray tube, and scanning is done electronically. The time-interval representing the azimuth of the sferics is coded in a binary system and transmitted immediately over the relay line to the central station. At this station, bearings received nearly simultaneously from a number of stations are plotted electronically as one sferics location. A complete scan and computation of a sferics position requires about 1/30 second. If three or more bearings fail to produce a small-enough triangle of error as set by the operator, the computer rejects the lot and tries the next set of data. This failure to obtain a fix may be due to radio signals from two lightning strokes getting into the system at the same time or to excessive ranges and distorted direction of arrival of sky-wave signals. Since sampling of every storm area within range is all that is required by the meteorologist, the loss of a small per cent of the sferics signals in this way represents no problem.

After testing a laboratory-built system, a service-test equipment was procured and delivered to the U. S. Air Force for test in September, 1959. The initial test of this system, centered at Kansas City, Mo., created quite a sensation among the meteorologists because it gave them an immediate picture of all lightning occuring over the plain states of the Missouri River Valley and indicated many frontal situations not appearing on the weather maps.

Let us now turn to weather observations over remote areas of the earth. Where habitable land areas cease, observation of the weather by the equipment previously referred to must also cease, except within the limited range of such equipment as weather radar and sferics. But the requirements of the forecasting meteorologist never cease until weather patterns are known the whole world around, or at least in his hemisphere, northern or southern. For observations over the ocean and in the Arctic, the meteorologist turns to ships at sea, weather reconnaissance aircraft, automatic weather stations, and the newest of all devices, still in its infancy, the meteorological satellite. USASRDL has played an active role in the last three named areas.

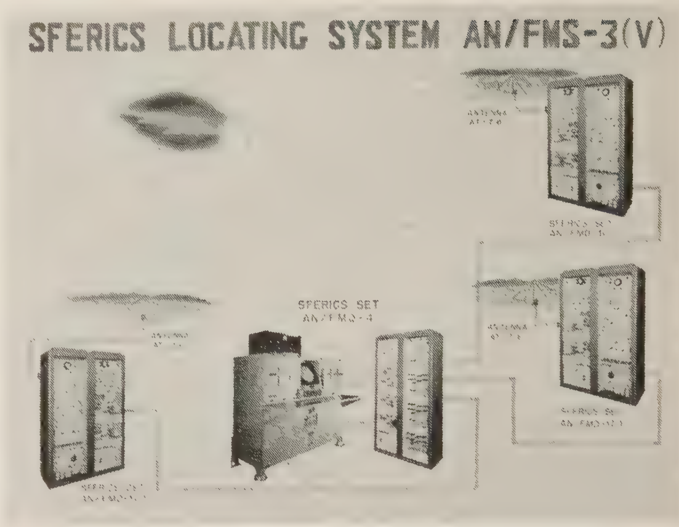

Fig. 19—Automatic sferics locating system.

To instrument weather reconnaissance planes, USASRDL developed the first parachute radiosonde to be dropped from weather reconnaissance aircraft in 1946. These radiosondes transmitted temperature, pressure, and humidity at 1.5 or 3 Mc in Morse code by use of a phonograph record and mechanical sensing elements. The data were recorded manually aboard the aircraft. In 1954 an audio-modulated dropsonde was developed to operate at 400 Mc out to a range sufficient to meet the needs of high-speed aircraft; the data were automatically recorded aboard the plane. For making observations from instruments mounted directly on the plane, aerographs were developed to measure and record temperature, humidity, pressure, wind speed and direction, and other meteorological data. L. Evenson was active in this area of research for many years.

For the observations of ground meteorological data on remote islands or barren wastes of the Arctic, an automatic weather station was developed by R. Boyd. In 1952 several of these stations were installed in the Arctic where they operated unattended for six months at a time, sending out weather messages over high-frequency radio links every six hours. In spite of this faithful performance, the problem of visiting, refueling, and servicing these stations every six months still represented a major obstacle to their more general use.

The meteorological satellite is the newest of all weather observers. It utilizes a large assembly of radio and electronic devices. There seems no point in describing this new addition to the family of weather instruments for it is surely quite familiar to all in general terms, and its evolution is too rapid to be recorded at this time as history. It promises, of course, to be a very valuable device for world-wide observation of weather situations. One of its earliest achievements has been the observation of cloud fields to a remarkable degree of completeness. It probably will be of great value in the

detection and repeated mapping of hurricanes, and it will also prove very useful in locating frontal systems with true beauty for the meteorologist.

I shall just mention two other very large areas where radio and electronic engineering are contributing much to meteorology. These are the fields of world-wide communications and automatic data processing. These areas will not be treated in detail because here the meteorologist is only one customer among many. Nevertheless, communications is the very foundation of modern meteorology, as pointed out at the beginning of this article, and the amount of data to be transmitted is constantly increasing. The transmission of weather maps by facsimile is one of the techniques of communication which have come into use in recent years.

Automatic data-processing is coming to the rescue of the meteorologist at a time when he sorely needs such help. The forecaster is fundamentally limited by the fact that he never has enough accurate data on the initial condition of the atmosphere to compute the condition at a later time and thus make a precise forecast. His efforts must always be limited to practical approximations. However, the continuous advances over the past 20 years in the techniques for sounding the atmosphere have provided much more accurate and greater quantities of data. Today the meteorologist receives not simply a surface weather map as he did in 1930, but he receives several weather maps for different altitudes up to 60,000 feet. He can also have weather radar data from many locations. In the near future he can expect also to have sferics data and data from meteorològical satellites. How can man use all these data to the full potential of their merit? Since 1957 he has been feeding part of these data into a machine at Sauteland, Md., to produce numerical predictions. This is the start of automatic data-processing for meteorological purposes on the grand scale. Far more of this automatic handling of data may be expected in the future.

In summary, the contributions of the electronic art to the field of meteorology have taken on a great variety of forms at USASRDL over the past 30 years. Equipments have been placed in operation at a great variety of frequencies in the electromagnetic spectrum from 10 kc for sferics direction finders up through the high frequency, VHF, UHF ranges, and finally arriving at 30 kMc for weather radar equipment. Seldom has the electronic engineer found himself pioneering in so many fundamental systems concepts as he was confronted with in finding optimum solutions to a great variety of measuring and surveying problems. At the beginning of this period the tools of the meteorologist were a few simple instruments such as barometers, thermometers, hygrometers, and simple balloons to be tracked with a theodolite. Today they include a great number of very complex electronic instruments. Truly, modern meteorology is indebted to the radio and electronic engineer to a degree comparable to that of the meteorologist. There is no doubt that the applications of electronics yet to come in this field will be quite as phenomenal as those which have already come to exist.

Radar Ballistic Instrumentation at White Sands Missile Range*

LYLE D. BONNEY†

Summary—**Early in the history of White Sands Missile Range a runaway V-2 missile indicated the need for better missile flight surveillance. Modified SCR-584 radars were soon after established as the basic source of surveillance data. Further modifications to the system made reliable all-weather trajectory data, readily achieved by radar. The development and implementation of the AN/FPS-16 radar at White Sands Missile Range represents the product of years of engineering to create a precision radar instrumentation system.**

"MISSILE AWAY" over the command net is the voice signal indicating that another test missile is now in flight. The attention of the instrumentation personnel, assigned to fulfill their varied tasks to obtain data, is now focused on the mission at hand. Askania Theodolite Operators, timing personnel, telescope observers, and radar operating personnel are busy compiling information which will become the history of the missile in flight.

The AN/FPS-16 radar is one of the primary sources of ballistic data at White Sands Missile Range. As the missile lifts from its launching pad the radar console operator watches as the ground clutter, consisting of numerous pips, resolves into a single pip which represents the missile. The tracking gate is brought into coincidence with the missile signal pip, and the rapid sweep of the gate is begun. Internal radar circuitry performs an automatic lock function, and the radar is now tracking the missile automatically. The digital data system associated with the radar is now recording ballistic data. The azimuth, elevation, and range data in binary code are

* Received by the PGMIL, July 11, 1960.
† U. S. Army Signal Missile Support Agency, White Sands Missile Range, N. M.

impressed upon magnetic tape, accompanied by the coordinating time code which is related to the time of the missile lift. The magnetic tape is also provided with tag signals necessary to read the data from the tape. Thus, the AN/FPS-16 radar begins another mission in support of the White Sands Missile Range.

Background

Behind the design and construction of the AN/FPS-16 radar is a story fraught with dreams, sweat, ingenuity, politics and confidence. The implementation of the missile range with eight of these instruments represents the fruition of twelve years of diligent engineering. The story began in April of 1946, when a task force from the U. S. Army Signal Research and Development Laboratory applied two modified SCR-584 radars to the problem of providing range safety for the firing of the German V-2 missiles at White Sands.

The first radar station at the Missile Range was located one mile south of the army block house (see Fig. 1). The station, in addition to the two radars, consisted of vans which contained the plotting boards, data recording equipment, and communication equipment.

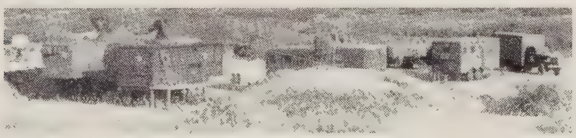

Fig. 1—"A" station, the first radar instrumentation at White Sands Missile Range. It was located one mile south of V-2 launcher.

The power for the equipment was provided by portable generators. From this simple beginning evolved the present chain radar system at White Sands Missile Range which employs the AN/FPS-16 radars. The increased firing rate of newly developed missiles required an increase in radar support. Missile firings which used the entire 100 mile range indicated the necessity for the development of a chain radar system. Five radar stations and numerous acquisition stations surrounding the impact areas were linked by such a system. Any tracking radar at any station could position the other radars and the Askania cameras associated with the impact areas on the missile in flight. Increased range support responsibilities included control of target drones by modulating the transmitted radar signal. On the advice of the operating personnel in the field, modifications were made to the basic SCR-584 radars to fulfill better the requirements of the new missile art. The range capabilities of the set were increased, the radio-frequency system was improved, and more powerful magnetrons were provided. Increased performance was the constant aim of the engineering support group. It became apparent that, in addition to the range safety mission, trajectory data could be provided quickly, and at low cost to missile contractors.

MPQ Modifications

The first modification contract, to enhance the support capabilities of the 584-type radar, led to the development of the MPQ-12 and MPQ-18 radars. Refinement in the local oscillator system, installation of tunable magnetrons, and an increase in the antenna gain were some of the modifications made to increase performance. A photographic data recording system was developed, in which data was recorded by photographing the elevation and azimuth cursor scales and the range cathode-ray tube presentation. The recorded angles and range were listed vs time for the data report. The accuracy of this system was 2.0 mils in angles, and 50 yards in range.

The last modification to the system, employing the basic 584, was the automatic data recording (ADR) system. This system employed a quantizer unit feeding the ADR equipment from which digital data was recorded on magnetic tape. The magnetic tape was then played into a high speed punch unit, which produced IBM cards, from which the listing was made. The automatic data recording system yielded an over-all accuracy of 1.5 mils in angles, and 20 yards in range, and it became the standard radar data source prior to the application of the AN/FPS-16 system.

In 1952, it became apparent that the refinement of the 584-type radar had reached its limit. Any further improvement would necessitate redesign of the entire system. The state of the radar art had advanced considerably since the original design of the 584-type radar. The application of improved components and design techniques promised a greatly improved system. Signal Corps personnel began preparing the specifications for an instrumentation radar.

The AN/FPS-16 Radar

In 1954, an instrumentation study contract between RCA and the Signal Research and Development Laboratory was negotiated. This contract was superseded by a tri-service contract, designed to meet the needs of the Army, Navy and Air Force. The AN/FPS-16 radar was the resulting hardware delivered on the contract (Figs. 2, 3, 4).

Installation of the first radar at White Sands Missile Range began in January of 1958. The delivery of eight more units followed on an approximate schedule of one every six weeks. Three such installations may be seen in Fig. 5.

In May of 1958, the first radar was completely integrated with the chain system, and was designated officially ready to support range operations. The initial evaluation of the system, personnel familiarization, chain integration and complex check out, had been completed. Calibration procedures and operational techniques were now standardized. Present radar locations are shown in Fig. 6.

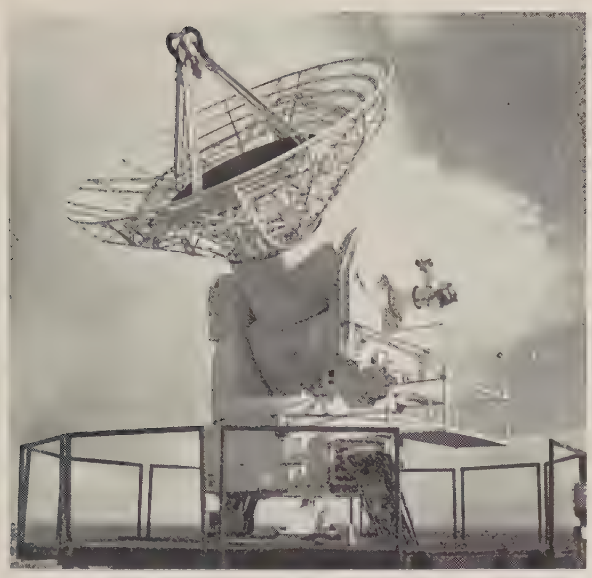

Fig. 2—Antenna pedestal of the AN/FPS-16 radar.

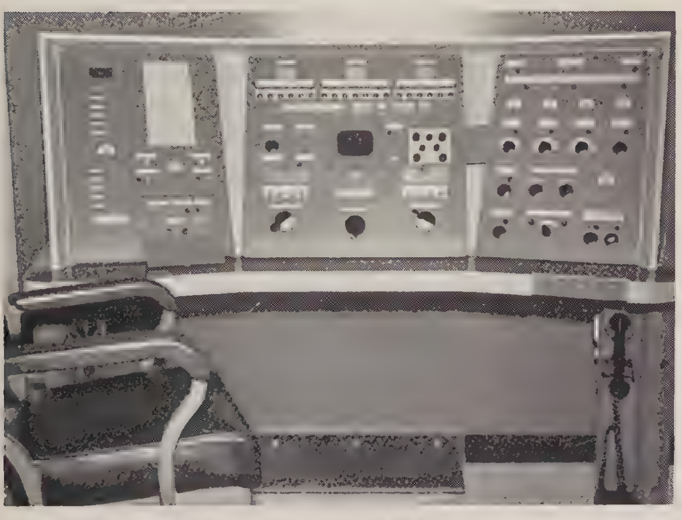

Fig. 3—Operator console AN/FPS-16 radar.

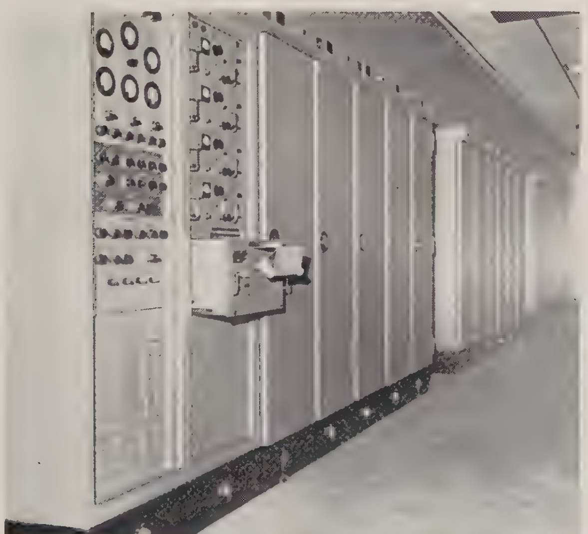

Fig. 4—Interior view of the AN/FPS-16 radar.

Fig. 5—The AN/FPS-16 radar installations at "C" station, located at the south end of White Sands Missile Range.

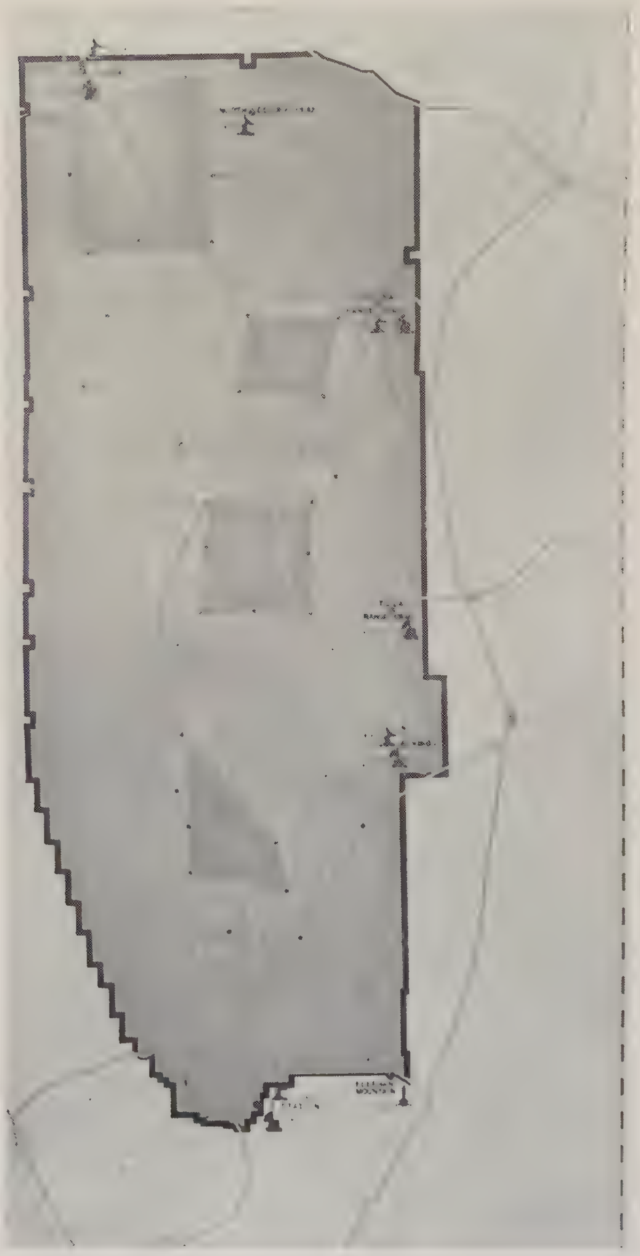

Fig. 6—Radar instrumentation at White Sands Missile Range. The symbols indicate the locations of AN/FPS-16 radars and MPQ-type radars, which are linked by the chain system. Shaded portions are the 30-, 50-, 70-, and 90-mile impact areas.

The quoted precision for the AN/FPS-16 instrumentation radar is 0.1 mil in angles, and 5 yards in range. The instrument operates extremely well under adverse weather conditions. When the missile being tracked is equipped with a transponder, it need not be seen visually to produce data of precise accuracy. The radar needs to be positioned remotely, only until the ground clutter has disappeared, in order to achieve automatic track prior to entry into the clouds. Of course, cloud attenuation is experienced in heavy storm overcast. Nevertheless, by employing the chain system to pass the target from radar to radar, as the missile progresses up the range, an adequate signal strength is maintained to produce a good track and quality data.

Since the radar system was completely new, very little statistical data was available regarding the accuracy of the system. The radar division of the Signal Missile Support Agency at White Sands, N. M., began a study to establish the accuracy of the new instrument as soon as it began taking data. All data that was obtained from the radar was compared to the data taken by Askania instrumentation. The magnitude of the difference between the two systems indicated 3.5 to 4.25 yards in range, and 0.15 to 0.29 mil in angles. The evaluation was based upon the data obtained from the first AN/FPS-16 radar in its first year of range support. Since the radar and the Askania accuracy are comparable, a continuation of the study, using two or more radars, is required. A program for the computation of multistation solutions by high speed digital computers is now being readied. This method will present a better indication of the over-all accuracy of the system.

Upon the completion of the mission, the tape is ready for delivery to the computer, along with the calibration data, which is applied as a correction. Because the digital data is recorded on magnetic tape, which is entered directly into the computer, the speed of reduction is extremely rapid. The data is not only reduced quickly, but is also done at 1/10 the cost of other methods.

Either the azimuth and elevation Selsyn data output from an optical tracker or the data from a three coordinate source can be used for the initial positioning of the instrument. When the optical tracker is used as the designation source, the console operator places his range gate to position it in coincidence with the pip desired. Should the designation data be in three coordinate form, both angles and range are positioned according to the data received from the acquisition system. An override feature is available if required. A scan feature designed to be used with the acquisition system aids in acquiring targets in this mode of operation.

The change-over time between missions is considerably less with the AN/FPS-16 radar than it is with other data systems, and if necessary, two or more missions can be recorded on a single reel of magnetic tape. Of course, adequate time is required to make the necessary calibrations to the system. Operations involving the use of a transponder require somewhat longer time in order to set frequencies and coding.

AN/FPS-16 Modifications

Three of the radars installed at White Sands Missile Range have been modified with three-megawatt transmitters. The same sets also have a data correction system installed. The modified sets have been placed at the south end, the north end, and in the center of the range, to utilize the higher power features. A complete evaluation of the modified system has not been completed. This evaluation will continue on the same basis as that of the unmodified instruments.

One radar at White Sands Missile Range is equipped with a million-yard range extension. It will be used in support of project Mercury and other satellite requirements. The instrumentation of these projects indicates several modifications of the equipment to aid in acquiring the target. At the present time, only one of the AN/FPS-16 radars at White Sands Missile Range will be used for Project Mercury.

In an effort to increase the capabilities of the radar system, studies are continuing to be made within the Signal Missile Support Agency and by RCA. It is felt that application of the system to range support will continually be increasing. New operational techniques and system improvements are being developed in the field to render the instrument more effective.

Future Developments

The transmission of data from the tracking radar directly to the computer is planned in an effort to make that data available to the missile contractor more quickly. This system expansion is especially necessary from the more remote tracking radars. A study contract which contemplates an entire instrumentation system to encompass the total support requirement of radar has been completed. The AN/FPS-16 radar is a vital link in the Advance Range Testing Recording and Control (ARTRAC) plan.

Conclusion

During the past 19 months, since the AN/FPS-16 radar has been in use at White Sands Missile Range, the Radar Division of the U. S. Army Signal Missile Support Agency has had an ever increasing feeling of confidence and pride in the instrument and its capabilities to accomplish a much needed instrumentation function of range support. As in all new systems, the advantages of the development will have to be pointed out to those responsible for the over-all instrumentation of the range. This can only be done by the continuation of the present statistical study of system evaluation. The potentialities for the application of the equipment are unlimited, but new concepts must be accepted to fully utilize the inherent capabilities of the AN/FPS-16 instrumentation radar.

The Development of a Dynamic Target and Countermeasures Simulator*

RICHARD L. NORTON†

Summary—**The Dynamic Target and Countermeasures Simulator described herein was developed at the U. S. Army Signal Missile Support Agency Laboratories, White Sands Missile Range, Las Cruces, N. M., by a group of Signal Corps engineers and technicians, utilizing components from scrapped radars and standard RF test equipment.**

This versatile simulator can be used to test existing radars for signal saturation and electronic counter-countermeasures techniques, such as regulating RF and video gain, contrast, etc. Provision is made to simulate antenna patterns and to vary the size of the target from 0.1 to 100 square meters.

The expense involved in training radar operators to cope with raids involving hundreds of aircraft has led to the development of various target simulators.

As the state-of-the-art in electronic countermeasures (ECM) improved, it became apparent that ECM simulation was also necessary to train radar operators under the conditions that would prevail when aircraft would be radiating thousands of watts of jamming power. Most of the simulators developed used IF or video injection of target signals in the simulator and did not provide the realism desired or allow the radar operator to exercise electronic counter-countermeasures (ECCM) techniques effectively.

The problem then became one of realistic simulation of both target and jamming signals. Field experience at White Sands Missile Range (WSMR) had demonstrated that simulation could be accomplished most effectively at the RF level. This finding, by WSMR engineers, led to the design and development of the Dynamic Target and Countermeasures Simulator.

Introduction

About two years ago, a group of engineers and technicians at the Signal Missile Support Agency Laboratory at WSMR started development of this simulator. The original model was considerably different from the present developmental model, since it was breadboarded from spare parts of salvaged radar sets and standard RF test equipment.

The model operated by receiving the transmitted pulse from the radar, time-delaying the pulse to simulate range, mixing it with an appropriate jamming signal, and transmitting the target and jamming signal back to the radar. Tests were conducted on a selected group of radar operators and the excellent results obtained indicated that further development was warranted.

After this technique was proven in the field by the Signal Missile Support Agency, it was turned over to Gilfillan Bros., Inc., Los Angeles, Calif., for further development and, finally, the fabrication of a mobile simulator unit. The present simulator is installed in a standard M-109 van which is a 12 by 7.5 foot inclosure mounted on a $2\frac{1}{2}$-ton truck chassis. The equipment provides for operation with L-, S-, and X-band radars.

As a training device, the simulator provides realistic target information in an ECM environment to such a degree that the radar system operators cannot distinguish any difference between a real and a simulated target. Comparison of operator proficiency can also be made by programming the same simulated aircraft course for different operators. In addition to its use for training, it also may be used as a radar system checkout device. Signal saturation level can be determined and the use of ECCM techniques, such as regulating RF gain and video, contrast, brightness, persistence, and luminescence, can be checked.

General Description

The complete simulator consists of a control console, PPI monitor scope, computer, RF assemblies, power supplies, and such minor subassemblies and couplings as are required to connect the equipment into the radar system. Fig. 1 shows part of this equipment. The PPI monitor scope, located above the control console, permits the simulator operator to monitor the operation of the radar L-band and S-band PPI scopes. Simulator video may also be observed.

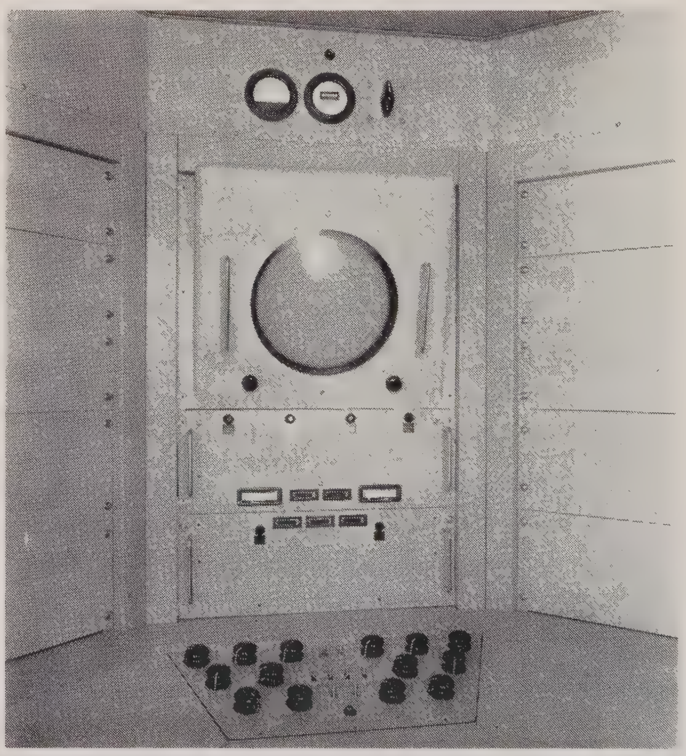

Fig. 1—Control console.

* Received by the PGMIL, July 11, 1960.

† U. S. Army Signal Missile Support Agency, White Sands Missile Range, Las Cruces, N. M.

Basically, the simulator is used in conjunction with a ground-based acquisition radar and target-track radar. The acquisition radar is supplied with a simulated target and jamming information through a directional coupler at the antenna. This allows the radar to operate normally, and since the antenna is revolving, ground clutter and actual moving targets will be seen on the PPI scope with the simulated target added.

The target-track radar receives its simulated data through a horn antenna mounted on the radar systems RF test mast. When the simulated target is designated by the acquisition operator, the target-track antenna slews to this beacon on the test mast. The target-track antenna will "lock on" to this beacon. Error voltages, which provide for apparent motion of the antenna, are then supplied by the simulator. In addition, circuitry is provided to cause the target-track radar azimuth and elevation indicator dials to register continuously the correct simulated target position. Operators will track normally and not be aware that the antenna is fixed in azimuth and elevation. During actual operations, the acquisition radar operator electronically designates any target on his scope and it will be transferred automatically to the target-track radar. Therefore, the operator may designate either a real or the simulated target and it will be transferred to the target-track radar. If the real target is designated, logic circuitry in the simulator disconnects the simulator from the target-track radar which allows the antenna to slew to the real target and track normally.

If either a simulated or a real target is transferred, the time from target designation by the acquisition operator to the time of target acquisition by the target-track radar operator can be measured for various operators to determine their proficiency.

TABLE I

Target and Jamming Source Parameters

Speed	0–2800 knots
Altitude	0–100,000 feet
Azimuth	0–6400 mils
Turn rate	0–6 degrees per second
Maximum range	150 NM
Heading	0–360 degrees
Jamming source power	1–100 w/Mc
Target radar cross section	0.1–100 m^2

Target scintillation and range attenuation ($1/R^2$ for the jamming source signal and $1/R^4$ for the target signal) are also provided. It is to be noted that only one target and one jamming source are provided in this developmental model. Both the target and jamming signal are independently "flyable" in heading, range, altitude, and speed. The simulator operator merely sets any initial courses desired and then programs these within the parameters already mentioned. Although one target and one jamming source are provided, the addition of any number of simulated targets and jamming sources is possible with very little increase in space requirements.

Control Console Operation

The control console (Fig. 1) has controls with which the operator can set the initial and flight conditions of the target and jammer. Initial conditions consist of the initial azimuth, altitude, and ground range of the target and jammer. Flight conditions are speed, turn rate, and heading of the target and jammer. Target area and jammer power controls are also provided. As a further aid to the simulator operator, dial indicators on the computer units, immediately above the control console, display the present range, elevation, azimuth, and heading of both the target and jammer. The PPI monitor scope, as previously explained, allows the simulator operator to monitor the acquisition radar PPI scopes as well as simulator video information.

Computer Operation

The computers for the target and jamming-source data generation are identical; therefore, the target computer will be explained as a matter of convenience. The computer is a combined static and dynamic coordinate-data generator, and the function of each section is outlined in Fig. 2. Initial conditions are set into the course generator when the simulator operator positions the appropriate control knobs at the control console. Initial ground range (R_g) setting, for example, provides analog voltages proportional to the starting position of the target in ground range. These reference voltages are applied to the input of a sine-cosine potentiometer. Selection of the initial target azimuth then positions this potentiometer by means of a servo mechanism.

The output of the potentiometer becomes R_g Sine θ and R_g Cos θ or, as shown in Fig. 2, $X_{T(I)}$ and $Y_{T(I)}$, the initial rectangular coordinates of the target. In the static mode, at any selected altitude, the simulated target can be initially located at a suitable range off scope, and programmed to "fly" into the field of view from any desired location.

Flight conditions which include target speed, heading, and turn rate are then set into the computer (Fig. 2). A similar sine-cosine potentiometer arrangement is used with the speed control providing analog voltages as inputs which are proportional to target speed. Target heading and turn rate then positions the potentiometer shaft through a servo mechanism. The output is the $\dot{X}$ and $\dot{Y}$ rate information.

When the simulator operator positions the Target Status Switch at "fly," $X_{T(I)}$ and $Y_{T(I)}$ (initial position of the target information), and $\dot{X}$ and $\dot{Y}$ (the rate information) are integrated. Rectangular coordinate data indicating the present position of the target, X_T and Y_T, are obtained.

The azimuth resolver section converts the rectangular

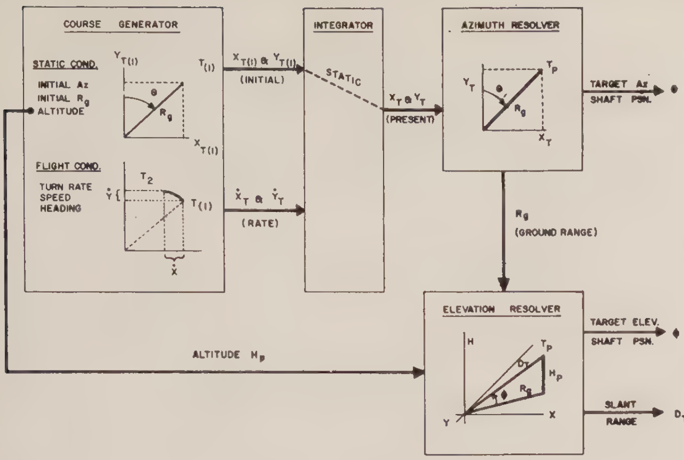

Fig. 2—Computer.

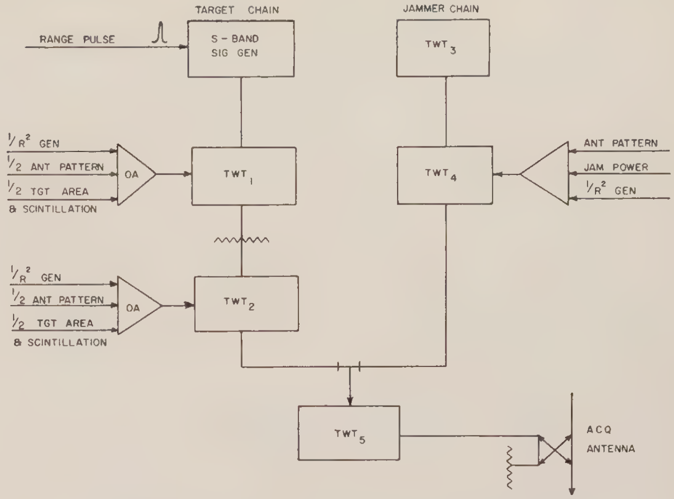

Fig. 3—RF assembly, acquisition radar.

coordinates of the target into polar coordinates, these being the present ground range (R_g) and the target azimuth (θ). Target azimuth is represented by the shaft position of the potentiometer and, as explained later, is used in azimuth gating of the acquisition radar target and jamming signals.

Present ground range (R_g) is supplied to the elevation resolver section, as shown in Fig. 2. This information, along with initial altitude data, set into the computer, provides the polar coordinate, slant range (D_T), and the angle of elevation of the target (ϕ). Slant range in the form of a dc analog voltage is then supplied to the precision range unit.

Operation of Range Unit

The precision range unit makes use of the Meacham system, which utilizes a quadrature phase-shift capacitor, to provide a jitter-free pulse-delay generator. Trigger pulse (preknock) is obtained from the radar system and supplied to a timing wave generator and a delay gate generator. Range delay in relation to the preknock is then obtained, based on the target or jammer slant range information from the computer. Pulses representing the proper range delay are transmitted through coaxial cables to the appropriate RF signal generator in the RF assemblies.

Operation of RF Assemblies

L-, *S*-, and *X*-band RF assemblies have been provided with this equipment. Since the *L*- and *S*-band assemblies are similar in operation, only the *S*- and *X*-band units will be discussed.

Fig. 3 illustrates the method used in providing RF target and jamming information. A considerable number of "off-the-shelf" items have been used in fabricating this simulator, including 13 traveling-wave-tube (TWT) amplifiers. Here, the TWT amplifiers are cascaded in both the target and jammer chains. Initially, the range pulse from the precision-range unit triggers the *S*-band signal generator to produce the RF target signal which is then amplified by TWT Number 1 and TWT Number 2. Both of these TWT's are modulated by operational amplifiers (*OA* in Fig. 3) with inputs from an appropriate network. The input provides for free space attentuation of the target signal, radar target cross-sectional area control (0.1 to 100 square meters), target scintillation, and antenna pattern simulation. Target range is attenuated inversely with the square of the range by TWT Number 1 and the output again similarly attenuated by TWT Number 2. The target signal, provided as input to TWT Number 5 has, therefore, been attenuated inversely to the fourth power of the simulated target range; TWT Number 5 provides signal amplification to compensate for attenuation in the coaxial cable to the acquisition antenna.

The jammer chain in Fig. 3 uses direct internal noise amplification of TWT Number 3 to produce broadband "white" noise. One hundred watts per megacycle jamming power can be obtained at a simulated range of three nautical miles. Here again, as in the target chain, variables such as jamming power (1–100 w/Mc), antenna pattern effects, and $1/R^2$ attenuation for the jammer range are summed and applied as modulation control for TWT Number 4. The particular technique of antenna-pattern reproduction provides realistic jamming presentation on the radar PPI scopes as the jamming power may enter the side and back lobes of the antennas.

The RF assembly for the target-track radar is slightly different from the acquisition radar arrangements, as shown in Fig. 4. As previously pointed out, the simulated target and jammer signals are transmitted from a fixed beacon. Antenna-pattern simulation is not necessary since the RF signals are transmitted through space to the actual antenna. During operation, the range pulse from the computer triggers a signal generator to produce the RF signal, which then passes through a ferrite modulator to provide target scintillation. Space attenuation is obtained by the use of two variable waveguide attenuators. The waveguide attenuators are positioned by a control motor which is operated by an

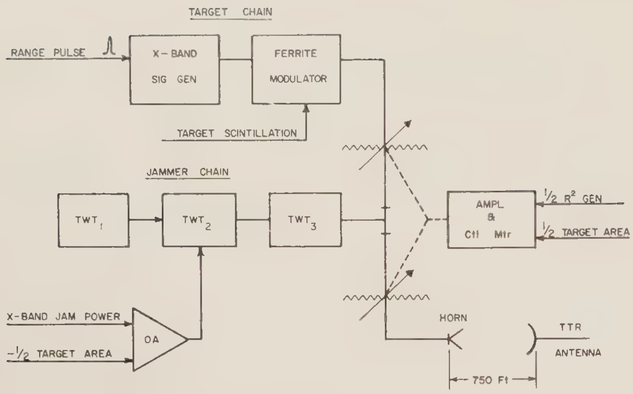

Fig. 4—RF assembly, target-track radar.

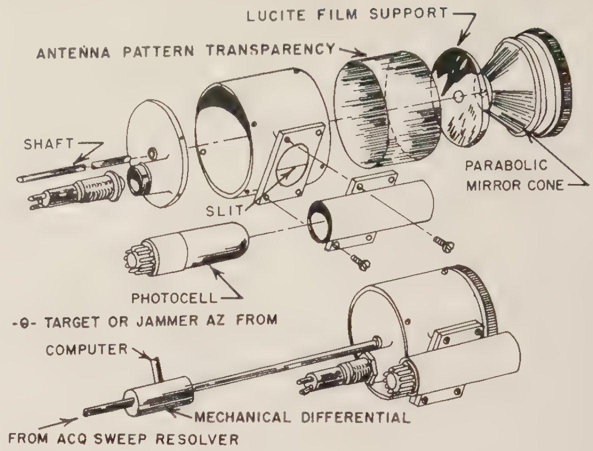

Fig. 5

amplified voltage inversely proportional to the square of the range, thereby automatically setting each attenuator to provide $1/R^2$ attenuation. Proper target or jamming-source signal attenuation is then secured by passing the signals through one or both attenuators as appropriate. Jammer chain operation, it will be noted, is similar to that employed with the acquisition radar.

As a point of interest, the $1/R^2$ voltage utilized for signal attenuation effects is obtained by supplying the computed target or jamming-source slant range voltage to a diode function generator. The output of this function generator is proportional to $1/R^2$ and is one input to the TWT driver amplifiers.

Target area and scintillation are provided through the use of a Rayleigh noise generator. The noise generator receives its input from the target-area control located on the control console. This control allows the simulator operator to select any cross-sectional area from 0.1 to 100 square meters to represent a specific missile or aircraft. The filtered output also provides the target scintillation effects. Here again, the output is used to operate the TWT driver amplifiers for TWT modulation.

Antenna Pattern Generator

The antenna pattern generator (Fig. 5) developed for use with this simulator provides realistic reproduction of the antenna patterns of the *L*- and *S*-band radar antennas. A variable-area photographic film is made of the actual antenna pattern. The film is then inserted in the generator unit and rotated in synchronism with the acquisition antenna. The main lobe on the film is offset an amount equal to the simulated target or jammer azimuth. A light source, projected through this rotating film, activates a photocell to produce a voltage inversely proportional to the antenna pattern. The amplified output is used to drive a TWT chain in the RF assembly. Excellent results have been obtained by use of this device since, as jamming power is increased, the jamming signal will enter the side and back lobes realistically.

Input information for the pattern generator is obtained from the resolver sweep circuit of the radar and from the simulator computer. Angular data relative to the acquisition antenna rotation are necessary if target information is to be presented at the proper azimuth on the radar PPI scope. These data are obtained from the radar resolver sweep circuit in such a manner that the antenna-pattern generator shaft will rotate in synchronism with the acquisition antenna azimuth scan.

A mechanical differential is driven at the same rate of rotation as the acquisition antenna, and the differential output shaft then drives the antenna-pattern generator. Film is thereby positioned so that the simulated target signal will appear in proper orientation.

Future Development

This present developmental model is now undergoing test and evaluation by the Army. The outcome of these tests will determine the future utilization and refinement of this equipment. In the design of this unit, cabinet space was allowed for future expansion which may include the addition of chaff generation equipment and an increased number of simulated targets and jamming sources. This could be the next step in the development of this simulator.

By slight modification of the control console, magnetic taped courses, in the form of standard operator electronic countermeasures tests, could be programmed and radar operator response recorded. Standard scoring on a comparative basis could be initiated for determining operator proficiency.

During the design and development of this simulator, every effort has been exerted to make target simulation and the jamming environment realistic. With the state of the art in countermeasures progressing at such a rapid rate, modern radar target simulators must be designed to allow the radar operator complete use of all electronic counter-countermeasures techniques available to him. Further, when the operator applies a specific countermeasures technique, the results obtained must be exactly the same as those obtained with actual targets in a similar countermeasures environment.

By providing realistic target and countermeasures simulation, radar operators can be trained effectively on a round-the-clock basis, with a considerable saving in manpower and money when compared to the cost of actual aircraft training missions.

The Signal Corps Role in the Development of Continuous-Tone Electrophotography*

E. K. KAPRELIAN†, SENIOR MEMBER, IRE, AND K. LEISTNER†

Summary—This paper discusses the reasons which lead the Signal Corps to investigate different nonsilver halide photographic processes, and to select electrophotography as the subject of a major research and development effort.

The problems inherent in the process are discussed and several methods with which it was attempted to evolve a workable procedure are shown. In particular, the research directed toward increasing the spectral response and over-all sensitivity of selenium layers, as well as of other semiconductors, is outlined. Other problems discussed are spontaneous decay of the charge in the dark, plate fatigue, and after-images. The different approaches to the conversion of the electrostatic latent image into a visible, permanent image are discussed, including liquid spray and immersion methods, dry "cascade" and powder cloud development. Emphasis in the discussion is on the powder cloud method and its related problems: selection of the most suitable powder material, uniformity of particle size, polarity and amount of charge of the particles, design of suitable cloud generators, particle agglomeration. It is shown that certain problems inherent in the powder development on selenium plates can be simplified by first transferring the electrostatic latent image from the reusable selenium to the permanent carrier, and developing on this carrier.

The paper finally discusses the possibilities for future developments and applications, and calls attention to a comprehensive list of pertinent patents available to readers on request.

Introduction

IN 1947, the U. S. Army Signal Corps undertook a survey of all known photographic methods and materials in an effort to determine what promise such methods might hold for military application. Although silver halide materials provide, now as then, the basis for the most widely used and universally applicable processes, they are not entirely free of disadvantages when used for military purposes. Therefore, the unconventional processes and materials were extensively investigated from the viewpoint of the requirements for employment under tactical and combat conditions: short processing time, absence of wet processing, long shelf life, freedom from fogging in a nuclear environment, and, hopefully, insensitivity to light except at the instant of exposure. All of these desirable characteristics were sought in a new process which was to possess the high sensitivity, panchromatic response, good continuous tone characteristics, and high resolving power of silver halide materials. A surprisingly large number of unconventional processes were found in the literature, and the more interesting of these were summarized in a subsequent publication by one of the authors.[1]

The Electrophotographic Process

Although no process was found which met the idealized requirements, electrostatic electrophotography was one of several methods which appeared to hold sufficient promise from both practical and theoretical viewpoints to warrant research support. In theory, it appeared that the resolving power could be very high, limited perhaps only by the performance of the image-forming optics. There was no apparent reason to doubt that high sensitivity and panchromatic response could be achieved. The practical aspects were also promising: it was a purely physical system; image processing should be achievable in a short time with a dry-powder developer; the plate had an indefinitely long life in storage and was reusable.

The state of the art prior to 1948 was essentially limited to the work of Selenyi[2–5] and Carlson[6–9] who described various means for producing an electrostatic image. Although electrophotography may take many forms, the specific electrophotographic system with which the Signal Corps activity was initially concerned employed a photoconductive film, now generally known as the Xerox process of the Haloid-Xerox Corporation. In this process, a thin vacuum-evaporated film of selenium on a conductive surface receives a uniform electrostatic charge in the dark. The dark resistivity of the selenium film, sufficiently high in darkness to retain the charge for a substantial length of time, is reduced several orders of magnitude when illuminated, and permits the surface charge to leak off to the plate. When a light image is received on such a charged surface, the charge leaks off proportionally to the intensity of the light in the areas corresponding to the image pattern, producing a "latent" image of areas of varying electrostatic potential. The latent electrostatic image is developed by dusting with a finely divided, pigmented, developer powder which has an electrical sign opposite to that of the charge on the plate and which adheres to the still charged areas to produce a visible image. This powder image is then physically transferred to a receiving surface of paper or other suitable base material and fixed to the base by heat or with an adhesive to form a permanent image. Still other forms of electrophotography were subsequently studied. These are also reported below.

Early Status

The Signal Corps' interest in electrophotography almost coincided with that of the Haloid Company in the

* Received by the PGMIL, July 11, 1960.
† USASRDL, Fort Monmouth, N. J.
[1] E. K. Kaprelian, "Methoden, Ergebnisseund Aussichten des Elektrostatischen Aufzeichnungsuerfahrens," *Photographic Eng.*, vol. 1, pp. 42–56; April, 1950.

[2] P. Selenyi, "A survey of photographic materials and processes," *Zeitschrift für Technische Physik*, pp. 607–614; December, 1935.
[3] P. Selenyi, "Application of electrography in television," *Wireless Eng.*, vol. 15, pp. 303–309; June, 1938.
[4] P. Selenyi, U. S. Patent No. 1818760; August 11, 1931.
[5] P. Selenyi, U. S. Patent No. 2143214; January 10, 1939.
[6] C. F. Carlson, U. S. Patent No. 2221776; November 19, 1940.
[7] C. F. Carlson, U. S. Patent No. 2277013; March 17, 1942.
[8] C. F. Carlson, U. S. Patent No. 2297691; October 6, 1942.
[9] C. F. Carlson, U. S. Patent No. 2357809; September 12, 1944.

Carlson patents; and in a short time, research to achieve acceptable continuous-tone results by direct exposure in a camera was being performed by Haloid and also by the Battelle Memorial Institute under a Signal Corps contract with the former. Concurrently, the laboratory began its internal effort, principally in the area of plate research.

The first plates, employing sulfur or selenium as the photoconductive layer, suffered from absence of red sensitivity, extremely low over-all sensitivity, poor tone rendition and nonuniformity of plate surface. The early results, of which Fig. 1 represents rather the best, could hardly be considered promising.

Achievement of practical results required extensive research in the following areas:

1) Plate improvement—learning the theory of plate behavior, increasing over-all speed, obtaining panchromatic response, achieving plate uniformity.

2) Developer improvement—learning the theory of developer behavior; exploring various developer materials and techniques, principally for obtaining continuous tone rendition and reversal development.

3) Transfer improvement—establishing techniques and image-receiving materials.

The plate research involved principally the use of selenium as the photosemiconductor with some additional effort directed toward organic compounds, phosphors, other inorganic compounds and dispersions of the latter in insulating binder materials. The research in development led to both positive image development and reversal development, while the work in image transfer involved not only the transfer of the powder image but also of the latent electrostatic image and included fixing of the image and cleaning of the plate.

Selenium Plate Research

In the work aimed at increasing the sensitivity of electrophotographic plates, two distinct periods can be seen, separated by several years in which almost the entire effort was devoted to other aspects of the process. The research of the first period, from 1948 to the middle of 1954, was stimulated mainly by results of investigation conducted internally at the Signal Corps Lab. (Squier Lab. at the time) by Keck.[10–12] It was shown that selenium, when coated at a temperature below 50°C, will be deposited in the vitreous form and have a spectral sensitivity in the blue and green region only, with a cutoff point near 560 mμ. Coating at higher temperature will result in a certain amount of crystalline selenium contained in the vitreous phase, the amount and particle size of the crystalline part depending also on the rate of deposition. The spectral sensitivity of layers containing a certain amount of the crystalline phase extends beyond 800 mμ with a pronounced minimum around 600 mμ. Keck also had shown that the addition of approximately 5–9 per cent Te to the Se will result in an increase in the photoconductivity, and a fair panchromatic response (Fig. 2). Much of the contractual work of this period, with the Haloid Company as prime contractor and Battelle Memorial Institute as subcontractor, was aimed at finding methods for producing selenium-tellurium plates consistently with reproducible characteristics of speed and spectral response. As was to be expected, the main difficulties arose in the method of evaporation. In addition to the obvious variables of the concentration of Te in the Se, the temperature and rate of evaporation, as well as temperature of the support plate during deposition, and numerous other technical details of the coating process were investigated. Studies were made of the treatment given the Se and Te prior to evaporation, and of the material, size, and configuration of the crucible; and methods for controlling and measuring the rate of deposition and the thickness of the coating were devised.

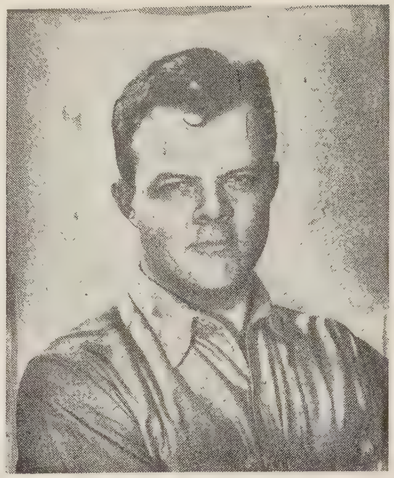

Fig. 1—Example of early electrophotographic prints (1948).

Although one-layer plates were obtained having up to 15 times the speed of pure Se plates, the reproducibility remained unsatisfactory. Furthermore, the gain in sensitivity was accompanied by an increase of the dark decay rate and the residual potential. It is obvious that a charged plate, given a certain maximum light exposure should lose its entire charge. It was found, however, that after several cycles of charging and discharging by heavy exposures, increasing amounts of charge were being retained, producing background "fog" after development and reducing the contrast of the image. Studies revealed that this residual potential is attributable to the presence of deep traps in the selenium.

The unsatisfactory results with one-layer plates lead to investigations of laminated plates having a basic coating of pure selenium of approximately 60μ thickness, and a top layer of either tellurium alone or a selenium-tellurium mixture. The thickness of the top

[10] P. H. Keck, "The electrical properties of selenium coatings," *J. Opt. Soc. Am.*, vol. 41, pp. 53–55; January, 1951.

[11] P. H. Keck, "Photoconductivity in vacuum coated selenium films," *J. Opt. Soc. Am.*, vol. 42, pp. 221–225; April, 1952.

[12] P. H. Keck, U. S. Patent No. 2739079; March 20, 1956.

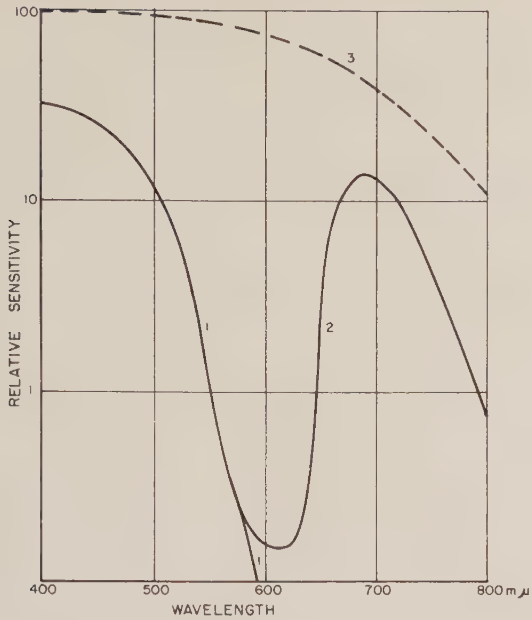

Fig. 2—Spectral response of amorphous Se (curve 1), amorphous +hexagonal Se (curve 2), and amorphous Se+7 per cent Te (curve 3), according to P. Keck.

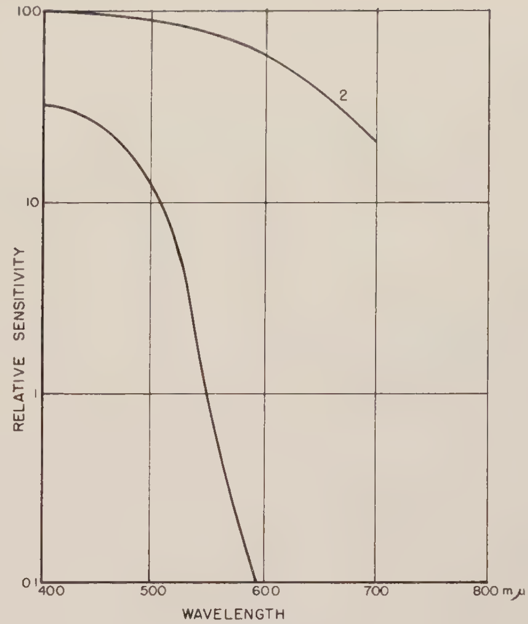

Fig. 3—Spectral response of two-layer, Se-Te plate, evaporated from separate boats (curve 2) compared with pure Se (curve 1).

layer was 10–20 per cent of that of the base. Results were more consistent, and the gain in over-all sensitivity in some of the best samples obtained was even higher than in the one-layer mixed Se-Te plates. The modified structure of the plates called for modified coating techniques. First the Se and the Se-Te mixture were evaporated successively from the same boat by keeping the Se-Te in a hopper during the initial phase, and dumping it into the hot boat after evaporation of the pure Se. Then two boats were used successively side by side, one containing Se, the other one the mixture. Finally two boats were tried with pure Se and Te, respectively. The cycle in the latter case required first evaporation from one boat, then from both simultaneously at properly balanced rates and temperatures. The spectral sensitivity curve of one of the best samples obtained is shown in Fig. 3 in comparison with that of pure Se.

At this stage, it became necessary to concentrate our entire effort on the problems of image development, "ghost image" prevention, and transfer of the image from the plate to a paper support. Further work on plate speed improvement was temporarily suspended.

The efforts aimed at increasing the sensitivity of the receptor were resumed in 1956. By this time, the Haloid Company had expanded considerably their research facilities and staff in the field of solid-state physics, and it was decided that further work should be done in Rochester.

A theoretical model had been conceived of the processes taking place in the electrophotographic plate, of the structure of an ideal plate, and the functions of its components. The model was based on energy-level diagrams and on concepts successfully proven in the development of the transistor. Prof. Bardeen, in his capacity as consultant to the Haloid Company, had been instrumental in clarifying and formulating these concepts.[13] The first phase of the new effort was aimed at attaining full panchromatic response, and reproducibly with a minimum of plate fatigue. Some of the knowledge gained during the work of the first period proved applicable to the new model, in particular the different spectral sensitivities of the amorphous and crystalline forms of selenium on the one side, and the optical absorptions of the two materials on the other: whereas amorphous Se absorbs strongly to approximately 650 mμ and shows little photoconductivity beyond 560 mμ leaving a gap of about 90–100 mμ, the crystalline form shows absorption as well as photoconductivity beyond 700 mμ. In order to make use of the extended response of the crystalline Se, a two-layered plate must be exposed from the crystalline side, otherwise the region between 560 and 700 mμ would be lost. On the other hand, the amorphous layer should be the carrier of the charge. These requirements are realized in the plate configuration shown in Fig. 4. A thin layer of crystalline Se is coated on a transparent conducting substrate, (*e.g.*, "Nesa" glass). On top of this, a film of amorphous Se approximately 50μ thick is applied. The exposure takes place through the glass. The spectral response of this two-layer plate is compared in Fig. 5 with that of standard xerographic plates on brass support. By use of a larger part of the spectrum, a gain of approximately six times over-all photographic sensitivity was achieved. It was, however, not only the peculiar configuration of this laminated plate which made panchromaticity possible. Just as with the

[13] For extensive bibliographies, see "Solid-State Electronics Issue," Proc. IRE, vol. 43; December, 1955; see especially: G. L. Pearson and W. H. Brattain, "History of semiconductor research," pp. 1794–1806; J. L. Moll, "Junction transistor dielectrics," pp. 1807–1819; A. Rose, "Performance of photoconductors," pp. 1850–1869.

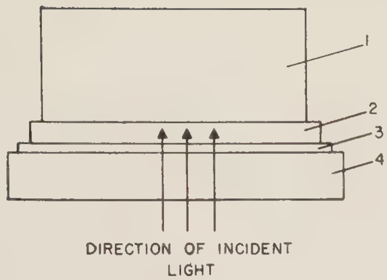

Fig. 4—Schematic model of panchromatic plate: 1, amorphous Se; 2, panchromatic photoconductor; 3, transparent conductor; 4, transparent substrate.

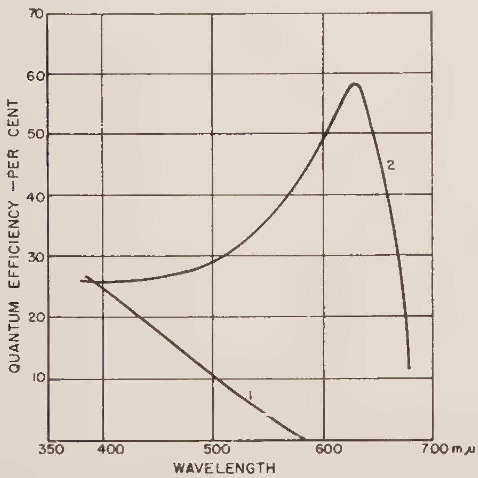

Fig. 5—Spectral response of plate according to Fig. 4 (curve 2), compared with pure Se (curve 1).

standard xerographic plate, the new panchromatic plate is given a positive charge for sensitization. This implies that negative charge carriers must move from the crystalline layer, *i.e.*, from the site of the exposure, through the amorphous Se in order to discharge the plate. This latter material is, however, primarily a p-type semiconductor. The Haloid Company had found that by proper doping, the conductivity type of amorphous selenium can be controlled, and it is such doped selenium which is used in the panchromatic plate.

The panchromatic plate does not exhibit the increase in dark-decay rate which was of great concern in the first work period. Other manifestations of "fatigue" were found, however. One has the effect that the time required for discharging the plate from a certain initial potential to a prescribed final value is increased by alternately charging and exposing the plate in rapid succession. This amounts to a loss in sensitivity, since longer exposures are required (for a given intensity) to produce a certain photographic contrast or potential difference. It was found, fortunately, that one can eliminate this fatigue effect by exposing the plate to higher temperatures during the operating cycle.

The second effect is the increase in residual potential after long and heavy exposures to light in the uncharged state, a treatment the plates may suffer during storage, shipment or handling. This does not seem serious in view of the fact that conventional photographic material is made entirely useless by exposure to light prior to the intended use. Nonetheless, the effect diminishes to some degree the inherent advantage of electrophotography over the silver halide process, that of "insensitivity" of the material before it is charged. The effect and means for its elimination are still being studied.

It must be emphasized at this point that the two-layered selenium structure which made a panchromatic plate possible may not be the final form for a high-speed plate. Different materials may be found for either or both of the layers, which may prove more effective than selenium. The development and extensive evaluation of the plate as described are of great value in any event, having served as a corroboration of the theoretical model on which the design was based. Its application to the next stage of the over-all effort now appeared justified.

The next step is obvious: the creation of a carrier multiplication effect in the plate. Presently, one photon can, at best, produce one hole-electron pair, and the electron can neutralize its equivalent charge on the surface of the plate. It is the goal of the investigations now in progress to devise a configuration of two (or more) layered materials which will permit a multitude of electrons to pass to the positively charged surface for every initial hole-electron pair produced. The mechanisms by which it is hoped that this will be achieved are "multiplication by trapping" and "*n-p-n* hook multiplication." The investigations required for the realization of these mechanisms are still in progress.[14]

Semiconductors Other Than Selenium

Although progress with selenium plates was rapid and sufficiently promising in the beginning, it appeared desirable to investigate the possibility of using other types of semiconductors. At a very early stage of the electrophotographic program (1949), contractual research was initiated at the Polytechnic Institute of Brooklyn under the guidance of Profs. Becker and Spoerri later joined by Prof. Ewald. This work was directed toward the photoconductivity of organic compounds and a fundamental understanding of the relationship between photoconductivity and the structure of organic compounds. The class of materials selected for most of this study was one of high molecular weight in which a tetracyclone group was connected by means of a bridge of conjugated carbon atoms with heterocyclic molecules. A representative member of this group, receiving particular attention, was 1, 2, 3, 4-tetraphenylcyclopenta-1, 3-diene. It was not possible to establish a complete correlation between structure and photoconductivity. It became obvious that the purity of the material was a major factor in the photo-conductive behavior. Anthracene, for example, which was also investigated, was found to equal selenium after being chromatographed three times. With some of the material, the experiments were

[14] Now under a joint Army/Navy contract NOas 59-6166-C.

carried to the stage of producing electrophotographic pictures. For this purpose, the samples were pressed onto aluminum plates, exposed, and developed by a powder cloud. Although some of the compounds showed promise with respect to photoconductivity, none, was found which combined all characteristics necessary for a workable electrophotographic plate. The difficulties of preparing the material, purifying it sufficiently, and coating it uniformly on a large area also were formidable. Efforts in this direction were discontinued, therefore, at the end of 1953.

Among the inorganic materials from which favorable characteristics with respect to electrophotographic applications can be expected, the phosphors must be considered first. From 1951 to 1953, Prof. Kallmann at the New York University conducted an investigation on "photoconductivity as a fundamental property of phosphorescent materials." A large part of the effort was devoted to the study of the "persistent internal polarization" effect discovered by Kallmann in the course of this work in 1953.[15]

It was found that certain materials, notably ZnS and organic phosphors, are capable of acquiring and retaining an internal polarization when they are exposed to light, while a dc electric field is applied across the sample. We can achieve this by depositing the material on a conducting glass plate and placing a second electrode (*e.g.*, a flexible aluminum foil) in contact with the other side of the coating. The exposure is made through the glass while the field is present. After the exposure, the field is removed and both electrodes are grounded while remaining in contact with the phosphor material. The internal polarization will persist for a long time; it is screened against external effects by the grounded electrodes.

If the aluminum electrode is removed, the internal polarization field can be detected by a probe, or can be made into a visible image by the normal electrophotographic developing methods, *e.g.*, by depositing a charged powder on the surface. The layer can be completely depolarized by infrared radiation, which is the basis for a number of variations of the basic process. It should be noted that the phosphor layer does not receive a surface charge, as with selenium, prior to exposure.

In addition to the work on persistent internal polarization, investigations were conducted aimed at developing a model of the processes occurring in photo-conductive phosphors. ZnS and CdS were used as prime representatives of inorganic compounds, while anthracene and chrysene were employed as examples of organic phosphors. It was concluded from the experiments that the photoconductive action in these materials is built up in three steps, the first of which is the filling of empty traps. During this period, only a certain portion of the excited electrons contribute to conductivity, and a slow buildup of conductivity occurs. This permits a rough estimate of the number of traps present. It was found that approximately 10^{14} to 10^{15} light quanta per square centimeter are required. This step seems to be more important in the inorganic phosphors than in the organic compounds. Inorganic phosphors, therefore, will show large photoconductivity only after a certain period. The second step in building up the photoconductivity is the creation of an internal polarized field. It was observed that it may take several minutes to develop the field to its final stage. This step seems to be of importance primarily in organic phosphors. A third step will occur only when the light does not penetrate the whole sample, but is absorbed in a thin layer adjacent to the surface. The step then consists of the injection of charges into the less excited portions of the sample. The finite time required for these steps to occur does not mean that the phosphor cannot be used during this time, it does mean that its sensitivity is reduced. Parallel to Kallmann's more fundamental study on phosphorescent materials went an effort at producing electrophotographic plates based on CdS and ZnS. Undertaken at Horizons, Inc., and directed by Dr. Eugene Wainer, this work extended over five years. After an exhaustive theoretical treatment of the subject, two approaches were tried, one using the material in powder form suspended in an organic binder, the other evaporating the phosphors onto a suitable support like aluminum.

For both cases, an extensive program on doping methods was carried out. For the powder material, Cu, Ag, Zn, and possibly Cd were found most useful, whereas Co proved to be a powerful poison for photoconduction. A basic difference was found in the behavior of these phosphors as compared to selenium. Whereas the charge on Se, upon exposure to light, will decay practically to zero in a few seconds, it first drops more rapidly with the phosphor, but levels off to a considerably higher residual potential. The peak of the photoconductivity lies in the range of 550 to 580 mμ. The results with the powder material were so poorly reproducible that this approach was abandoned. In the preparation of broad-area evaporated-ZnS/CdS layers, problems were encountered similar to those found by Battelle Memorial Institute and Haloid in the production of the selenium-tellurium plates. The composition of the material deposited on the substrate tends to be different from that in the boat or crucible at the beginning of the process. Modes of operation were developed for controlling the rate of evaporation of each component, and for maintaining the desired amount of doping. In the case of ZnS plates, doping with lead was most successful, Fig. 6. Post-evaporation heat treatment, and oxygen annealing proved effective in many instances.

In addition to CdS and ZnS, Horizons also investigated the possibility of improving the characteristics of selenium layers by including arsenic. Coatings were made by evaporation having compositions ranging from 2As·3Se to 3As·3Se. No clear correlation between As

[15] H. Kallmann, U. S. Patent No. 2845348; July 29, 1958.

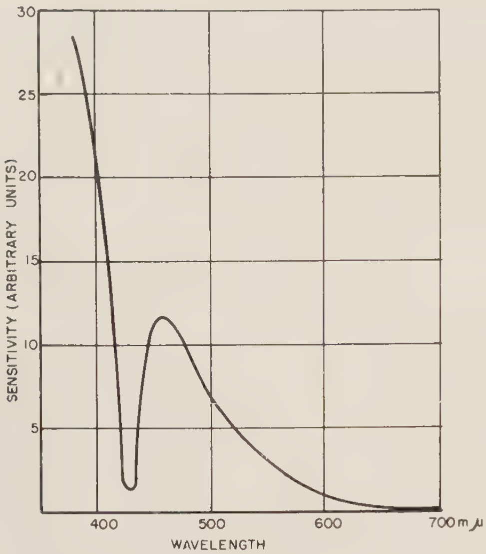

Fig. 6—Spectral response of evaporated ZnS, doped with PC.

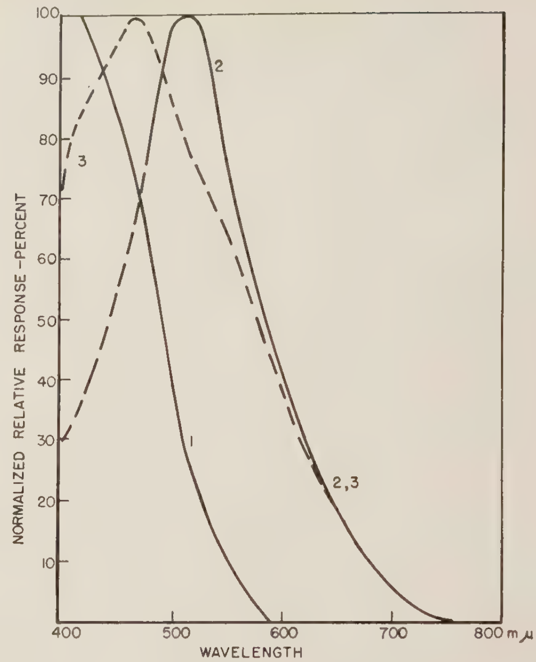

Fig. 7—Spectral response of Se·As plates: curve 1, pure Se; curve 2, 0.5As·3Se; curve 3, 2As·3Se.

content of the layer and photo conductivity was found, although as a general rule the amount of initial charge retained and the dark decay half time decreased with increasing As content. The spectral responses of two sample plates are shown in Fig. 7. The results of the evaporated plates also were not very well reproducible and it was recognized that a more basic study of the evaporation technique for this type of compounds was required. Furthermore, by the time the work on the last contract with Horizons had been completed, it had been decided to resume an intensified effort aimed at increasing the speed and spectral response of the selenium plate. As a result, the work on CdS layers was terminated.

A short investigation was also made to determine whether or not selenium can be deposited in a useful form by electrolysis from solution. Since the required amorphous selenium has a high dark resistivity, electrodeposition of this material almost seemed a self-contradictory requirement. No previous attempts were found in the literature. Dr. Graham of Graham, Crowley and Assoc., Inc., Chicago, Ill. (later Graham, Savage and Assoc., Inc., Jenkintown, Pa.), and his co-workers kept the cathode of the electrolytic cell under constant illumination during the electrolysis. It was possible to deposit amorphous selenium layers, the outside appearance of which did not differ from selenium deposited by evaporation. X-ray diffraction tests proved their amorphous form, and spectral analysis indicated a high degree of purity. They were deposited from a bath containing 350 g SeO_2/ liter and a certain amount of wetting agent, the p_H was held at 0.8–1.0, the temperature at 75°–110°F. With a current density of 0.1–0.3 amp/dm^2, layers of approximately 30μ thickness were deposited in five to six hours on a substrate of electroplated bright nickel. Unfortunately, the charge retention of all samples was almost immeasurably short. Considerations based on experience gained during the concurrent contract at Haloid Xerox Inc. lead to the conclusion that the production of suitable selenium plates by electrodeposition is not very likely to succeed. The work in this field was therefore discontinued.

The application of electrophotography to continuous-tone reconnaissance imagery seemed to depend entirely on the use of homogeneous layers of such photoconductors as Se or CdS. The system using discrete powder particles in a binder, known as "Electrofax," had not shown any indication that it would produce true continuous tone of the required density range and tone gradation, at least not up to approximately 1957. The attempts made with ZnS and CdS in a binder during contract DA 36-039 SC-15435 with Horizons, Inc., did not advance to the stage where continuous-tone reproduction could be tried. It was recognized that Electrofax would have its place, however, in facsimile recording, if the sensitivity could be increased sufficiently to permit the required writing speed. For this purpose, the Signal Corps initiated research at the American Photocopy Equipment Company, Evanston, Ill. (APECO), and the Armour Research Foundation of the Illinois Institute of Technology, Chicago, Ill., as subcontractor, with the purpose of achieving panchromatic response of the ZnO as well as increased over-all sensitivity. ZnO can be dye-sensitized similarly to AgBr, some of the known photographic sensitizers also being effective with ZnO. In addition, several hundred dyes were investigated by APECO and a substantial increase of the spectral response was achieved. Since ZnO grows in different crystallographic forms, their relative capability for absorbing dyes was investigated. No significant differences were found. The desired increase in quantum yield was attempted in essentially three ways. First, several

elements were tried as doping material for ZnO powder. The difficult task of doping the minute powder particles was approached by evaporating the material onto ZnO spread out in a thin layer, shaking the container to expose new surfaces of the ZnO, evaporating again, and so on several times. At the end of this cycle, the coated ZnO was heated to 495°C. It was found that only Al enhanced the photoconductvity, and only by a factor of 3; no increase in quantum yield was found. The second approach was based on the consideration that the photoinjected carriers can modulate the height of interparticle barriers which control the current flow. If each particle can be coated with a layer of insulating material, a high barrier will be created prohibiting electron transfer. Holes created by photon absorption and captured by the barrier will lower it and increase the probability of interparticle electron transfer. ZnO powder was prepared, each particle of which was covered with a monomolecular layer of insulating material; an example of an organic material employed is $(CH_3)_3$ SiCl. It was expected that this material would react with OH present on the surface of the ZnO to form HCl and the desired hydrocarbon monolayer, a reaction known to occur on quartz and glass surfaces. Inorganic materials such as Silane and Diborane were also tried in an effort to form a layer of SiO_2 or B_2O_3. Unfortunately, none of the samples showed an indication of barrier modulated photoconductivity. A third approach attempted to establish ohmic contact of the ZnO particles by dispersing mercury around and between the particles. This was achieved by ultrasonic techniques. An increase of photoconductivity was not observed.

Sensitizing

Electrophotographic receptors are made sensitive by applying a positive or negative charge uniformly to the surface of the receptor. The method used almost universally is that of a corona discharge; ions are produced around a wire carrying a voltage of about 7000 volts, and are driven towards the receptor by the field between wire and surface. Approximately 10^{12} ions per cm^2 are required to produce this charge. The corona device requires a power unit uncomfortably heavy for certain applications like portable cameras. Charging by means of radioactive material was investigated, therefore, by two of the Signal Corps contractors. Radium, as contained in an "IONOTRON," Sr^{90} and $Polonium^{210}$ were tried by Haloid in 1952, and Po^{210} again by APECO /Armour in 1957. In both cases, sources of approximately 15 to 20 microcuries were used. The time for charging is longer than with the corona wire: a 15 microcurie source will charge one square inch in about 13 seconds. An electric field is still required to force the ions produced down onto the surface. The rather small advantage, combined with the possible hazard in the handling of radioactive materials resulted in termination of further work in this area.

Image Development

The latent image on the electrophotographic receptor is made into a visible and permanent image by depositing light-absorbing particles in the desired areas. In the cases where no "negatives" are produced in the sense of conventional photography, *i.e.*, when a heavily exposed area of the receptor is expected to appear lighter in the image than one with a low exposure, the particles must be deposited on the residual charge. This is the normal, straightforward case of electrophotography, and one of its advantages is that it does not yield a "negative" which requires a further step in order to produce a positive image. However, one important Signal Corps application required that electrophotographic prints be made from negatives obtained by the conventional silver halide process. For this application, a reversal development had to be formed, details of which will be discussed later. In order to achieve high resolution and a smooth appearance of the image either in the case of normal development or of reversal development, the particles must be very fine, preferably having a size of a few microns. These particles can be transported and brought in contact with the surface of the receptor by these basic methods:

1) By attachment to larger carrier particles which physically touch the receptor and transfer the fine powder.
2) By suspension in a liquid which can be sprayed onto the receptor. The liquid must be a good insulator, and should be highly volatile so that the droplets have almost evaporated when they arrive at the receptor, leaving the surface substantially dry. Alternatively the liquid can be brought in contact with the surface by means of rollers, or the exposed receptor can be submerged in the liquid.
3) By suspension in air, thus forming an aerosol, which is blown against or along the surface of the receptor.

Method 1 has found two embodiments in the "cascade" and the "magnetic brush" development. In the first case, the carrier particles are glass beads, usually coated with material which stands higher in the triboelectric series than the powder material. They are rolled across the surface of the selenium plate or drum or the electrofax sheet, thereby charging the fine powder triboelectrically and transferring it to the exposed areas. This is the standard developing method for "line work" such as printed material, drawings, etc. In the "magnetic brush," the particles are attached to iron filings which, in turn, are held in a lump at one pole of a magnet. This device is moved, brush-like, across the surface of the receptor, transferring the powder particles to the image areas.

In the course of the research and development work for the Signal Corps projects, all these methods have

been tried more or less extensively. For continuous-tone reproduction of subjects in which almost the entire image area assumes some tonal value, leaving only relatively small portions "white" (aerial photographs, for example), the aerosol method has been most extensively used and investigated. Liquid suspensions also yield excellent continuous-tone pictures as shown in particular by Australian workers.[16–18] Because of certain operational considerations the Signal Corps asked for an aerosol method in their equipment development. "Powder clouds," as these aerosols are usually called, can be produced by numerous methods, and many different devices were built and evaluated during a development contract with Haloid-Xerox aimed at printing equipment, and during research concerning developing and transfer techniques (Haloid Xerox and Battelle Memorial Foundation). It may suffice to indicate some problems and one successful solution. The powder particles must assume a charge opposite to that on the surface of the receptor. The triboelectric charging method which emerged from many experiments as the most widely used will not impart the desired charge to all particles. Those charged oppositely will increase the ever-present tendency to agglomeration, leading eventually to clogging of tubes and making purging of the system necessary. The powder in the cloud generator must be metered properly to keep the density of the cloud at a constant level. Electrophotographic images tend towards an overdevelopment of edges and underdevelopment of the interior of large areas. An analysis of the electrical field distribution over partly charged areas reveals the reason for this phenomenon, and also suggests means for controlling it. In many cases, this "edge enhancement effect" is very desirable, while in other applications it must be suppressed. In a design finally adopted for printing equipment, the powder cloud travels from a generator through tubing, one portion of which consists of a specially selected ceramic material. It is by contact with this material that the triboelectric charging takes place. The powder cloud enters a chamber which leads into a narrow slot extending over the entire width of the plate to be developed. The plate moves across the slit parallel to a stationary "development electrode," a large-area electrode spaced a few thousands of an inch from the moving plate. The powder cloud enters this narrow space with low velocity; the powder is not blown against the plate, but settles on the exposed area slowly, under the influence of the electric field between the electrode and the selenium plate. Large plates may require several development slots in succession to build up sufficient density. A density of approximately 1.8 can be achieved with this arrangement.

[16] K. A. Metcalfe, "Xerography," *J. Sci. Instr.*, vol. 32, pp. 74–75; November, 1955.

[17] K. A. Metcalfe and R. J. Wright, "Liquid developers for xerography," *J. Oil and Colour Chemists Assoc.*, vol. 39, pp. 845–856; February, 1956.

[18] K. A. Metcalfe and R. J. Wright, U. S. Patent No. 290–7674; October 6, 1959.

Reversal Development

Early attempts at reversal development of selenium plates were made by using white developer powders and transferring the developed image to a dark support member. For many reasons, this method was not satisfactory, and means had to be found to force the conventional dark powder to settle down most densely in areas devoid of charge. Two conditions of the developing method previously described must be changed to achieve this goal. First, the usual connection of the development electrode to the back side of the selenium plate is changed by inserting a dc source at this point so that the development electrode assumes the polarity of the charge on the surface of the receptor. The voltage is made to equal that of the highest residual charge. The second condition is that the powder particles must have (predominantly) the polarity of the surface charge. Above an image area with maximum residual potential, which previously had attracted most of the powder, there is now no field at all, and no powder will be deposited. Between an area devoid of charge and the development electrode, a strong field exists forcing a large amount of powder onto the receptor. The voltage applied to the development electrode cannot simply equal that of the initial charge of the receptor. Between charging and development some dark decay takes place. The highest residual charge must be measured, therefore, and must be measured in as short a time as possible, lest further dark decay occurs. Special rapid-action scanning equipment was developed for this purpose in order to insure that the voltage applied to the electrode equals that of the maximum residual charge within fairly narrow limits. It can be easily seen what the result will be if the potential of the electrode is either higher or lower: if higher, no truly white areas will appear anywhere; if lower, white areas will occur where some medium grey should be, and areas which should be white (possessing the highest residual potential) will assume a light grey produced by attracting powder of the opposite polarity. It must be realized that by triboelectric charging the entire powder cloud never takes on only the desired polarity—a certain percentage of particles of the opposite polarity are always present.

Although reversal development of Electrofax-type material was not the subject of Signal Corps research and development, it should be mentioned in the interest of completeness of the present report, that in the reproduction of line work a reversal is readily achievable.

For continuous-tone images on selenium, the reversal process has been worked out quite efficiently. At an early stage of the development, it appeared desirable to explore a different approach to the problem of reversed images. The selenium plate was exposed, without being charged, in an electric field. The image-wise exposure caused different degrees of conductivity in different areas, and the surface assumed a modulated charge by induction. When the field was removed after the exposure the charge remained and was developed. To produce a field during exposure, a transparent electrode

had to be used above the selenium layer, practically in contact with it. Nesa glass was found well suited for this purpose. It does, however, absorb some of the incident light, and calls for increased exposure. Because of this and other difficulties this otherwise interesting method was not pursued to any great extent.

Image Transfer

One of the main characteristics of electrophotography on selenium (or other large-area homogeneous semiconductors) is the reusability of the receptor. This implies, if a permanent image is desired, transfer of the developed image to a suitable carrier. In the beginning of the development, it was felt that any paper material could be used, and for the crude pictures of the early days any reasonably smooth paper was sufficient. As the quality of the developed continuous-tone pictures improved, the demand upon the characteristics of the transfer paper became more stringent. An almost perfect transfer, with very little powder remaining on the selenium, can be made with moist "dye transfer paper," a paper with a coating of clear gelatin. Although relatively little pressure is required, this method is not suitable for mass production. Most of the work in connection with Signal Corps contracts was done with polyethylene-coated paper. The coating provides a smooth surface, insuring good contact with the plate surface. It also has a softening temperature well below that where paper becomes charred, a characteristic important for the subsequent step of fixing of the image by heating. Whereas for line work the developing powder usually is a resin with a low melting point, the most suitable developer for continuous-tone images has been shown to be charcoal powder. Since this, unlike the resin, cannot be softened for permanent binding to the paper, it was necessary for the paper to have a coating capable of performing this function. In addition, the high dielectric constant of the polyethylene paper is an important advantage. It had been attempted originally to achieve transfer merely by applying pressure to the selenium plate and transfer paper by means of rollers. The high pressure required for good transfer tended to cause damage to the selenium coating. It was found that the pressure can be reduced far below the danger point when the transfer is effected in an electric field, the polyethylene coating of the paper assisting in achieving adequate field strength. The seemingly simple transfer process held numerous problems for research and development, centering mainly in the requirement for complete transfer in order to achieve satisfactory maximum density of the image.

Transfer of Electrostatic Images ("TESI" Method)

In 1954, L. E. Walkup, J. F. Byrne, *et al.*, working at Battelle Memorial Institute on subcontract for the Haloid Company, proposed investigation of a modified transfer method. Instead of developing the image on the selenium plate, and transferring the powder to the paper, the new method was to transfer the residual charge onto polyethylene-coated paper and develop the image on the paper. This mode has two advantages; it eliminates the necessity for cleaning the plate to remove residual powder, a step which frequently had been the cause for minute scratches and other blemishes of the plate; and, in addition, the charge is no longer subject to dark decay once it is transferred to the non-conductive paper. The "TESI" method was investigated and a laboratory model based on this principle was built under contract DA 36-039 SC-64600 (1955–56) (Fig. 8). The

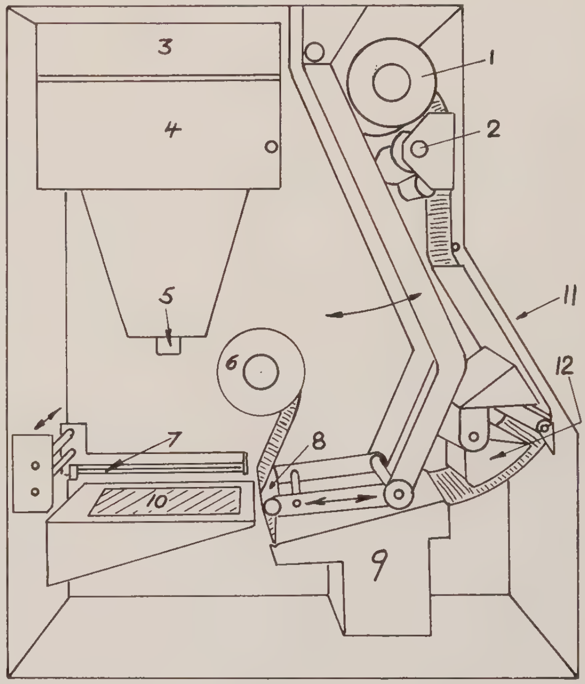

Fig. 8—Schematic diagram of the "TESI" printer-processor: 1) take-up spool, 2) transport rollers, 3) lamp house, 4) negative holder, 5) lens, 6) supply spool of polyethylene-coated paper, 7) corona charging unit, 8) transfer roller, 9) development unit, 10) selenium plate, 11) viewing window, (12) heat fuser.

selenium plate (10) in this equipment is stationary in the focal plane of an enlarging lens (5) and receives its charge from a corona charging unit (7) moving across the plate from one side. After exposure, the paper is brought in contact with it from the other side from a supply roll (6) by means of a reciprocating roller (8) which also serves as an electrode. The field built up between the roller and the plate, as the former moves across the plate, causes the charge to transfer from the plate to the paper. The paper then passes through a powder cloud development stage (9) and a heat fusing device (12). The model proved the soundness and practicability of the principle. Because of other more urgent tasks, the development of the model was not carried through to a field unit. The importance of this method for the future may lie in its application to images on thermoplastic film, as in the interesting process recently developed by the General Electric Co.[19]

[19] W. E. Glenn, "Thermoplastic Recording," *J. Appl. Phys.*, vol. 30, pp. 1870–1873; December, 1959.

Fixing and Cleaning

The powder image on the paper can be easily wiped off unless it is fixed in position, usually done by heating, as indicated before. Since not all the powder is transferred to the paper, the selenium surface requires cleaning. Air (*i.e.*, vacuum cleaner or blower) is not sufficient. During the equipment development work (Contract DA 36-039 SC-64465), rotating soft fur brushes proved most effective. Those operations complete the processing cycle of the selenium plate, which now is ready to be charged for a new exposure. Fig. 9 shows an example of the quality of images which can now be obtained by this process.

Electrophotographic Patents

As is the case with many other technical fields, the principal source of specific information regarding the materials, techniques and apparatus for electrophotography is to be found in the patent art. Some measure of the accelerating interest in electrophotography is to be found in the fact that of the approximately 300 U. S. patents issued, over one-half have been granted in the past two years.

Principal assignees of these patents are Haloid-Xerox, RCA, IBM, General Dynamics and the U. S. Government. In addition to those patents assigned directly to a government agency or granted under title 35, there are a number of others resulting from government-supported research and development under which the U. S. Government enjoys a royalty-free, nonexclusive license.

The authors have prepared a list of U. S. patents relating to electrophotography by number, inventor's name, date of issue and assignee, together with a brief description of the invention to guide those who desire further information, and also to indicate the activity in this field. This list, not published here in the interest of conserving space, is obtainable upon request from the authors. A few of the more interesting foreign patents for which no corresponding U. S. patent has been issued are included as an appendix to the list.

The Future

The past ten years have seen the application of electrophotography to duplication of line copy, radiography, facsimile, multicolor printing, microfilm card printing, galvanometer and cathode-ray tube recording, printed circuit production, color photography by color separation techniques, and address label printing.

If the progress in the past is a measure of its future rate of advance we may expect during the next ten years:

1) resolving powers of several hundred lines per millimeter, making possible high reduction xerographic microfilms with conventional applications as well as "live" microfilm systems in which a record card or strip is kept current by the addition of new images;

Fig. 9—Electrophotographic print from silver halide negative, 1960 status (courtesy Haloid-Xerox, Inc.).

2) good continuous tone rendition combined with high resolution, opening the way to motion picture printing and other high performance photographic applications;
3) high panchromatic sensitivity combined with high resolving power and good continuous tone rendition, making possible direct photography and motion pictures as well as in direct sound track recording, and
4) new techniques and materials resulting in direct full color photography, either additive or subtractive.

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Trends in Army Signal Corps Research and Development Procurement*

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Summary—**Signal Corps and general military electronic R&D procurement is undergoing continuing evolution in technology, techniques and controls, which have direct influence on industrial planning, management and operations. The close partnership of military and industry requires cognizance of and response to these pressures. Systems procurements generate the industrial "team effort" approach. Small business is gaining a strong foothold in the R&D effort through diversity of electronic research.**

Certain aspects of R&D are stimulating a limited move towards greater use of fixed price contracts. New trends have effect on industry approach to preparation of bid proposals and the military techniques of evaluation. Engineering efforts require management comptroller surveillance to avoid cost problems. Over-runs in cost contracts are being subjected to increasing military controls and limitations with serious effects on contractor management techniques. Contract management in industry is evaluated in terms of effective response to procurement trends.

Introduction

THE function of Signal Corps Research and Development procurement may be described as providing a vehicle for the transition of a set of desired military characteristics, based on concept or theory, into tangible hardware by means of an advancement or break-through in the state of the art.

In 1908, the Signal Corps contract with the Wright Brothers for a military aircraft accomplished this objective with a simple one-page contract for a fixed price of $25,000 to be paid if the aircraft reached an airborne speed of forty miles an hour. In the post-Pearl Harbor months, millions of dollars for R&D were obligated and expended with hardly more initial formality.

However, the fifteen years since the end of World War II have seen significant changes in Signal Corps R&D procurement with continuing effects on the industry-military team.

The spectrum of electronic research has undergone tremendous expansion and is still mushrooming at a fantastic pace. As a result, research funds are being dispersed over an ever-widening field, while rising overhead and direct costs are cutting the purchasing power of the dollar. The rate of advancement across this entire spectrum also has achieved phenomenal pace, creating faster obsolescence rates and sharply reducing the allowable time frame for transition from concept to hardware.

As these factors have channeled more and more defense dollars into research and development, the Department of Defense has developed increased management controls for insuring effective use of public funds. These are reflected in close scrutiny of programming of expenditure and effort, more sophisticated and complex R&D procurement procedures, and careful monitorship of program progress vs costs.

Industry and the military function as an inseparable team with the common objective of providing the best in military electronics for national defense. For this team effort to be effective, there must be complete understanding and coordination between members.

It is particularly important that industry, both engineering and management, fully understand the implications of these trends and their meanings with relation to participation in, and benefits from, R&D procurement.

A dominant factor of importance to industry is the increasing need for active management participation and competitive business methods in R&D. Brains, imagination and ingenuity are still the basic keys to electronic progress, but they no longer stand alone as the primary criteria. The pressure for active aggressive management methods stems from within industry itself as well as from governmental trends.

While there are many more fields of interest, the walls separating the known from unknown are becoming more penetrable. To an increasing degree, the key to advancement in a given field lies primarily in the amount of dollars and effort applied. These manifold fields of interest have spurred an era of specialization which new small firms have utilized as a springboard for launching themselves into a strong competitive position.

With constant and continuing progress opening new markets in both defense and commercial development, independent research (both fundamental and applied) has become the keynote of progress in electronics.

Effect of Systems Procurements

A major stimulus to management's importance in research and development is the complex "systems procurements." New military concepts encompass equipment configurations which involve the marriage of several electronic fields of interest, and in some instances, combine electronic skills with those of other basic arts such as aviation, ground support equipment or ordnance.

Examples of these are the AN/MPQ-32 (Radar Artillery Locator System), the AN/USD-4 and 5 (combat surveillance drone systems) and UNICOMM (an integrated communication system incorporating automatic switching and storage characteristics). The complex technical requirements of the equipments, involving the marriage of several scientific fields, virtually preclude the feasibility of any single industrial source providing all the know-how for complete development.

* Received by the PGMIL, July 11, 1960.

† Commanding Officer and Deputy Commanding Officer, respectively, U. S. Army Signal Supply Agency, Fort Monmouth Procurement Office, Fort Monmouth, N. J.

DEPARTMENT OF THE

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...gnal Corps, United States Army.

These Articles of Agreement entered into this ------tenth-------- day of February--, nineteen hundred and-eight--, between ----Chas. S. Wallace----, Captain-----------------, Signal Corps, United States Army, of the first part, and

Wilbur and Orville Wright, trading as Wright Brothers, of 1127 West Third Street, Dayton,

in the county of--------Montgomery----------, State of------Ohio----------- of the second part. Witnesseth: that in conformity with copy of the advertisement, specifications, and proposal hereunto attached, and which, in so far as they relate to this contract, form a part of it, the said -------------------Chas. S. Wallace, Captain,---------------- Signal Corps, United States Army, for and in behalf of the United States of America, and the said -------------------------Wright Brothers------------------------ (hereinafter designated as the contractor) do covenant and agree, to and with each other, as follows, viz:

Article I. That the said contractor shall manufacture for and deliver to the United States of America,

One (1) heavier-than-air flying machine, in accordance with Signal Corps Specification No. 486, dated December 23, 1907.

Art. II. That the deliveries of the supplies and materials herein contracted for shall be made in the manner, numbers, or quantities, and for each number or quantity, on or before the date specified therefor, as follows, viz:

That complete delivery shall be made on or before August 28, 1908.

Art. III. All supplies and materials furnished and work done under this contract shall, before being accepted, be subject to a rigid inspection by an inspector appointed on the part of the Government, and such as do not conform to the specifications set forth in this contract shall be rejected. The decision of the Chief Signal Officer, United States Army, as to quality and quantity shall be final.

Art. IV. That for and in consideration of the faithful performance of the stipulations of this contract, the contractor shall be paid at the office of -----the Chief Signal Officer-------------of the Army--------- at -----Washington, D. C.--- for all supplies and materials delivered in conformity with the requirements of this contract, on or before the dates above specified (Article II. *supra*) *and accepted*, the following prices, viz:

One (1) heavier-than-air flying machine at a total cost of twenty-five thousand (25,000) dollars.

to be paid as soon as practicable after the acceptance of the same, in funds furnished by the United States for the purpose, reserving per cent from each payment until final settlement, on completion of the contract or otherwise.

Art. V. It is further agreed that for all supplies and materials which shall not be delivered in conformity with the requirements of this contract on or before the dates prescribed therefor in Article II, above, but which shall be subsequently delivered and accepted, the prices shall be as follows:

within the time and in the manner specified above, Articles I to III, inclusive, the said party of the first part may, instead of waiting further for deliveries under the provisions of the preceding article, supply the deficiency by purchase in open market or otherwise, at such place as may be selected (the articles so procured to be the kind herein specified, as near as practicable); and the said contractor shall be charged with the increased cost of the supplies and materials so purchased over what they would have cost if delivered by the contractor on the date they were received under such open-market purchase.

Art. VII. It is further agreed by and between the parties hereto that until final inspection and acceptance of, and payment for, all of the supplies and materials and work herein provided for, no prior inspection, payment, or act is to be construed as a waiver of the right of the party of the first part to reject any defective articles or supplies or to require the fulfillment of any of the terms of the contract.

Art. VIII. The contractor further agrees to hold and save the United States harmless from and against all and every demand, or demands, of any nature or kind for, or on account of, the use of any patented invention, article, or process included in the materials hereby agreed to be furnished and work to be done under this contract.

Art. IX. Neither this contract nor any interest herein shall be transferred to any other party or parties, and in case of such transfer the United States may refuse to carry out this contract either with the transferor or the transferee, but all rights of action for any breach of this contract by said contractor are reserved to the United States.

Art. X. No Member of or Delegate to Congress, nor any person belonging to, or employed in, the military service of the United States, is or shall be admitted to any share or part of this contract, or to any benefit which may arise therefrom.*

Art. XI. That it is expressly agreed and understood that this contract shall be noneffective until an appropriation adequate to its fulfillment is made by Congress and is available.

Art. XII. That this contract shall be subject to approval of the Chief Signal Officer, United States Army.

IN WITNESS WHEREOF the parties aforesaid have hereunto placed their hands the date first hereinbefore written.

Witnesses:

John J Mullaney as to } Chas S Wallace
Albert Lanwere as to } Signal Corps, U. S. Army.

C E Taylor as to } Wright Brothers
H G Hoffman as to } by Orville Wright

Approved: , 190

James Allen
Brigadier General,
Chief Signal Officer of the Army.

*Here add to any contract made with an incorporated company for its general benefit the following words, viz: "But this stipulation, so far as it relates to Members or Delegates to Congress, is not to be construed to extend to this contract." See section 3740, Revised Statutes.

(Executed in quintuplicate.)

Fig. 1.

These systems requirements have brought about the "industrial team effort" concept in procurement.

A special system of solicitation has been developed for the systems type procurement. Selection of sources is made from firms having extensive experience and background in one or more of the major fields involved. A presolicitation conference is then held which may be attended by potential team members and subcontractors. It is specifically noted that there is no limitation on the number of sources which may combine in the team effort in prime-subcontractor relationship in the subsequent submittal of proposals.

In the team concept approach, a single firm assumes the function of team leader (prime contractor), assembles the subcontract team, prepares the proposal reflecting a coordinated course of action; offering a technically acceptable approach, and assuring complete systems responsibility and control. Basic considerations in government evaluation of team effort proposals are: qualifications and experience in systems engineering, programming and budgeting. Upon award of a systems contract based on team effort, the prime contractor functions as a team manager in the complete development and ultimate assembly of the equipment. Full responsibility for performance in accordance with the terms of the contract rests with the prime contractor; including, in some cases, the underwriting of the responsibility of subcontractors in a weak financial position.

Small Business in R&D

A phenomenon of the evolution in electronics research and development is the effect on small business firms which, until recent years, occupied an urchin-at-the-window position.

Diffusion and depth of electronic inquiry have served as basic stepping stones for increased participation of smaller firms in R&D. Diversity of interest has brought intensive specialization within a number of fields of interest; the resultant dispersion of funds has assisted in bringing the scope and dollar level of a greater number of projects within easier reach of qualified small business firms.

Even the massive systems type procurements have been beneficial to small business in their extensive technical subcontracting capabilities.

There is an infinite variety of prime contractor R&D effort open to small business firms in electronics; including specialized studies, component development, fabrication of test items, etc., in addition to the subcontract opportunities at first and second tier levels within industry's military prime contracts.

Trends in Contract Types

It is not unusual for today's industry to receive requests for quotations on R&D projects which ask for offers on a fixed price basis (with or without redetermination) with cost-type proposals as an acceptable alternate.

This does not mean that the cost-type contract is not a preferred form for research projects with an inherent major risk factor involved. It does mean, however, that the Signal Corps is carefully screening projects with regard to the amount and degree of complexity of R&D involved, and its potential relationship to the over-all costs. In a growing number of cases, technically sound, acceptable fixed-price proposals are received. This indicates that independent fundamental research, in some cases, places certain firms in an advantageous position to insure both performance and price on advanced-type projects.

The Signal Corps' investigation of R&D fixed-price contracts follows a determined trend in the Department of Defense toward firmer budget control and forecasts of anticipated expenditures. It also reflects a specific reaction against costly over-runs on prior year contracts which constantly siphon away current year funds.

These are considerations which top management should study carefully in both current operations and future programming, particularly with respect to the value of independent research.

Preparation of Bid Proposals

The preparation of bid proposals on research and development projects has become an exacting art in its own right, directly influenced by the trend factors discussed above. The Signal Corps is today seeking answers to many questions which are incidental to the technical problem itself, but which have important bearing on the degree of success of the ultimate contract.

Typical of the facts demanded for evaluation are: who are the engineering and scientific personnel, top management and key supervisors, and what is their caliber of experience in the field? Does the technological approach show a complete understanding of the problem in all aspects, and does it give assurance of definite performance on schedule? Is excessive R&D cited, considering the industry-wide state of the art? Is engineering cost and effort commensurate with the technical approach? Are the material costs reasonable? Is the overall price high, or is the cost so low as to indicate a lack of grasp of the technical complexities, underestimation and a potential over-run?

In addition, if the solicitation involves a systems-type procurement, adaptable to industrial team effort approach, the proposal must include special factors evidencing degrees of system engineering background, projected management and coordination procedures, evidence of adequate program organization and integration.

It is obvious from these factors that technical capability alone is not the primary element in R&D contract evaluation, and the engineer cannot function as the

dominant character in preparing proposals. He must work as a part of a highly skilled management team, which must package an offer which is not only technically satisfactory, but which offers assurance of accomplishment through sound, capable management, with an attractive and realistic price tag attached.

Prominent in the team's mind must be the fact that sole source and limited solicitations are becoming less frequent. Competition of a number of firms carefully pre-screened, with regard to technical capability, is probable. While cost is normally a secondary consideration to that of adequate performance in R&D cost-type contracting, it becomes a decisive factor where more than one technically acceptable proposal is under consideration. This may be even more important as a consideration when the project has a tie-in with independent commercial research and product application, and competition is keen; in such cases fee or direct costs may be shaved commensurately by some firms.

Firms which have enjoyed prior dominance in their field of interest should beware of over-complacency in preparing their proposals; this is a transient factor which is subject to rapid change in the electronic industry. It is a particularly dangerous element of dependency for firms whose self-assumed superior technical qualifications are modified by a history of limited achievement, cost-over-runs and/or delayed delivery. The Signal Corps and the military, in general, give these past performances increasingly close scrutiny, and there is free interchange of data within technical services and between military departments.

Techniques of Proposal Evaluation

The Signal Corps is particularly cognizant of the cost and effort expended by industry in preparation of bid proposals, but it is doubtful if industry is equally aware of the extensive and detailed mechanics of the military evaluation of them.

The evaluation team consists of both procurement and technical personnel, each with its own subteam of specialists.

The technical evaluation is performed by government technical experts and scientists, drawn from research facilities such as the U. S. Army Signal Research and Development Laboratory, but may include special members from other technical services or military departments. The complement is especially selected to cover each specialized field of technology involved. Prior to receipt of proposals for evaluation, the project is reviewed by the technical team project leader, who establishes areas of evaluation, and the criteria for each. An engineering determination is made according to the weight that is to be applied to each area and element. The evaluation factors are tailored to each procurement, and seldom identical in value. To insure complete impartiality in any two procurement competitive proposals, codes are customarily assigned to the proposal (reviewed, evaluated, analyzed) by each technical member or subgroup to conceal the identity of the individual firms. Upon completion of the technical area evaluations, the proposals are reassembled for a final composite evaluation and recommendation. The final technical evaluation report limits itself to technical considerations only, and cost is specifically excluded.

The procurement team element takes over next, and conducts a three-phase evaluation with regard to the pricing factors, business analysis, and contractual aspects of the proposal. Business analysis inquiries involve past performance data, financial responsibility and stability, and adequacy of management and organization. It is in pricing analysis, perhaps, that the most intensive probing is conducted, with special attention being paid to both positive and negative data. Overhead, direct costs, and fees are principal areas of interest, and here a special review is made of the firm's past pricing history on all of these elements; recent changes are examined for cause and justification. Direct costs receive special inquiry with regard to appropriateness of direct labor and effort to the technical requirements, for herein may be a key to a potential over-run in costs.

Upon completing these evaluation phases, the proposal packages are ready for final comparative evaluation by the Contracting Officer and negotiation team, with regard to technically responsive bidder or bidders with whom negotiations shall be conducted.

The Engineer Team: Government and Industry

In evaluating R&D trends, the place of the engineer calls for some special attention. The brains and imagination of the engineer are the basic keys to performance; however, without effective management surveillance, the engineer may be as much a source of problems as the answer to them. As has been mentioned, government emphasis today is on timely progress and accomplishment. With fewer unknowns and more certainties in forecasting achievable advances, the government expects that industry will perform within the cost confines of the contract. In many cases the failure to perform in accordance with cost estimates is directly traceable to engineering approach involving both government and contractor personnel.

While specifications for research and development can never be completely definitive, every attempt is made to express (at a minimum) specific basic performance characteristics and levels. Nevertheless, engineers, both government and contractor, in their earnest quest for optimum solutions, often tend to overshoot the performance objective and "gold-plate" projects with desirable characteristics not basic to performance.

Many firms still follow the practice of placing R&D contract responsibility on engineer dominated management; with a basic responsibility of insuring technical

accomplishment, and with little or no responsibility to, or monitoring by, a comptroller. Contract administration and controls are thereby relegated to subordinate supporting status. This practice permits technical changes to be incorporated without close evaluation of contractual cost effect. In some cases, technical changes are costed on an individual basis, without a full evaluation of subsequent overhead and direct cost effects resulting from delays or changes in direction or associated subcontracts or primary contracts. As a result, funds are prematurely exhausted short of project accomplishment.

The engineer project manager who fails to monitor engineering effort and costs carefully, in terms of the specifications, may find his firm saddled with what is essentially an expensive, partially-completed piece of junk. Contract over-runs are no longer automatically funded to completion. At best, an over-run may mean a stoppage with internal dispersion, and sometimes loss, of key engineering personnel. A temporary stoppage may further evolve into a project cancellation, solely on the basis of prohibitive additional start-up costs rather than the merits of the nominal over-run funding originally required.

Cost Over-Runs in R&D Cost Contracts

The most distasteful term in R&D military procurement today is "cost over-runs." Under present Department of Defense R&D management procedures, any price increase on previously funded and budgeted projects can only be resolved by elimination or trimming of current year projects. Normally, over-runs are also accompanied by some form of delay in completion of the project.

In past years, when costs were lower and the spectrum of effort more restricted, it was customary to hold contingency reserves which could be used to fund project extensions to completion. Today, the Department of Defense operates its R&D program on a businesslike basis akin to an industrial comptroller-type operation. While research and development can never be considered an exact science, some of the aura of uncertainty in procurement techniques has been removed by experience and advancement in the state of the art.

Improved methods of preparing requirements and solicitations and in precontracting evaluation have done a great deal to eliminate the underestimation of costs from R&D procurements *as originally conceived and stated in requirements.* (It must be admitted, however, that mutual underestimation of costs by both military and industry remains a factor, particularly in projects demanding basic advancement or breakthrough in the state of the art.) Experience has demonstrated, however, that over-runs in cost contracts usually may be traced to specific tangible conditions in the course of contracts *after award.*

Principal problem sources may be generally identified as changes in military requirement, over-refinement in engineering approach, accretion of nonproductive direct costs due to delays, poor coordination, or changes in direction of effort. Some of these elements are inherent in R&D since the rapid changes in the state of the electronic art, and in military requirements, must be considered in the progress of any project.

The Signal Corps is refining its procedures for monitoring and restricting engineering changes to the necessary minimum, on a continuing basis. However, certain factors are beyond government control without close, responsive coordination on the part of industry. For instance, the estimation of an engineering change cost is normally based upon direct cost factors, inclusive of general overhead costs.

Usually unknown, and not made a point of consideration in estimation and negotiation, are the hidden costs such as latent, inherent delays, or costs on subcontracts or secondary disruption due to reprogramming in terms of effort and time. These are normally reflected in subsequent side effects such as increased overhead or distributed direct costs across a variety of categories. Changes, therefore, often have a "ripple effect" considerably beyond their obvious direct costs, which become apparent only in delayed evaluation of total program progress and cost. Within military procurement there is growing conviction that "no cost change" is a purely illusory term in research and development.

The delay in evaluating the cost deviations with respect to performance progress is further compounded where contractor cost reports are maintained solely on a payment basis without some analysis at total commitment status. This is a subject of major import to both the government and industry. When contractor project management records are based on progress of actual cost payments, it is difficult for the contractor (and impossible for the government) to determine the adequacy of initial funding balances at any given stage. This situation often results in delayed detection of an additional funding requirement.

Since funding of over-runs must be submitted, in most cases, at a reprogramming level, quick reaction funding is virtually impossible. If supplementary funding requests are submitted too late in the fiscal year, a carry-over of programming and funding to the next fiscal year is probable at best. In almost all such late detection cases, some form of work disruption is involved, such as scaled down effort or temporary or extended work stoppage. Work stoppages involve the need for still more funds (because of start-up costs), and often cause a breakup in skilled project teams. While this presentation is directed at the problems of the military-industry team in meeting R&D defense objectives, it is obvious that over-runs have a drastic effect on industry itself, involving both prime and subcontractor. It is a matter of serious mutual concern not only to avoid over-runs, but to maintain a progress surveillance sys-

tem to detect and forecast the extent at the earliest possible time to minimize effects on both military and industry.

The Signal Corps has found that the best method of timely analysis of funding problems is one based on a comparison of *commitment dollars* to progress. The difference in analysis by commitments and by actual paid costs is roughly analogous to that between the family checkbook and the monthly bank statement. In the management control and analysis of contract by commitment, all actions which reflect outstanding payments against available contract funds are regarded as expenditures. Under this system, a one-million-dollar subcontract would be considered as an expenditure on the day it is signed, even though payments would be phased over several months. The same would be true of material on order, salaries payable, etc. Each of these represents a lien against the total contract dollar authority.

A true commitment report normally runs not only far in advance of payments, but also somewhat in advance in actual work progress. However, any error factor is on the positive side of alerting attention and action.

This method of reporting expenditures vs progress for program analysis is being injected into Signal Corps R&D contract monitoring procedures, However, it is a system that should not be treated solely as a military requirement, but as a valuable technique for internal contract management.

Influences on Industry Contract Management

What are the implications of these trends on R&D contract management and how can industry best respond to their pressures?

First of all, there must be authoritative direction and surveillance emanating at top management level, and lines of communication between the operating level and management must be unimpeded. Operational control and responsibility must be vested in a central authority, exercising a comptroller-type function over engineering effort, costing and contract administration. Control procedures and analysis techniques for centralized authority must be accurate, sensitive, and timely. Lateral communication and coordination between engineering, costing, and contract administration must be on a team basis with direct contact.

It would seem logical that large firms with the greatest experience in R&D would exhibit the most effective and advanced techniques in contract management. However, Signal Corps records conclusively show that firms of moderate size consistently exhibit the best performance within original cost and time estimates, with minimal contractual difficulties.

An analysis of the organizational structures of these firms seems to offer only one clue to this phenomenon—simplicity. They have grown large enough to develop organizational depth, strength and balance. They have not reached the point of excessive depth within organizational layers; vertical structures are still simple enough to afford close lateral contact.

In brief, organizational structure of the moderate size still retains the essential characteristics of the close-knit team effort concept, represented in the basic requirements cited above.

Contributing to the validity of these observations is the experience of the Signal Corps in systems type procurements. Prime contractors are normally among the larger industrial firms. Because of the inherent complexities of these systems, in most cases, a special internal organization is established as a semiautonomous unit, reporting to a single authority at top management level.

Here again, efficiency in contract management is noteworthy as compared with industry as a whole.

Conclusion

This paper has been aimed at focusing attention on some of the significant transitions in electronics R&D, in the hopes of serving, to some degree, the maintenance of that high level of understanding and coordination which so far has characterized the Signal Corps-industry defense team alliance.

The accelerating pace of the electronics sciences and its parallel demands on military strategy and tactics calls for the utmost in unified effort.

It is the objective of the Signal Corps R&D effort to insure that this nation maintains an advanced electronics position which meets all defensive requirements with an effective safety margin. The effective achievement of this position within the availability of funds, and with maximum regard for the United States taxpayer's purse, is the obligation and deep concern of Signal Corps procurement operations.

Contributors

Isidore Bady (A'43–M'54–SM'56) was born on July 21, 1913, in Brooklyn, N. Y. He received the B.S. degree from the College of the City of New York, N. Y. in 1933, and the M.E.E. degree from the Polytechnic Institute of Brooklyn, N. Y., in 1949. He is currently working towards a Doctors degree at Rutgers University, New Brunswick, N. J.

I. Bady

He has been employed by the Signal Corps at Fort Monmouth, N. J. since 1941, where he first worked on instrumentation for the evaluation of components and materials. The frequency range covered was from dc through microwaves, including pulses. For the past four years he has worked in the field of magnetic materials, particularly ferrites.

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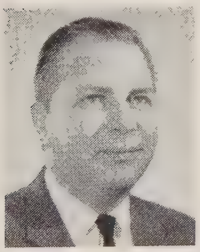
Isidore A. Balton (M'55) was born on August 4, 1914 in Philadelphia, Pennsylvania. He received the B.S. degree from the College of the City of New York, in 1934, and the M.S. degree in education from the School of Education, College of the City of New York, in 1946.



I. A. Balton

From 1942 to 1947, he was an instructor of electronics at the Air Force Technical Training Command, Scott Field, Ill.; at Yale University, New Haven, Conn.; at the Eastern Signal Corps Training Center, Fort Monmouth, N. J.; and at the U. S. Maritime Service Institute, Sheepshead Bay, N. Y. In 1947, he was appointed Registrar of the U. S. Maritime Service Institute, a government correspondence school that provided technical training to merchant seamen. He returned to the Signal Corps in 1954 as a publications writer in physical sciences and engineering, and he is currently on the technical staff of the Institute for Exploratory Research, USASRDL, Fort Monmouth, N. J.

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Gordon W. Bartle was born in Utica, N. Y., on January 15, 1907. He attended Syracuse University, N. Y. and then Columbia University, New York, N. Y., for a total of three and a half years, majoring in physics.

He then served with the Bell Systems, for twelve years as a switching engineer, specializing in electromechanical automatic switching equipment. In 1941, he joined the U. S. Army Signal Research and Development Laboratory, Fort Monmouth, N. J., where he was first chief of a section of the Communications Department concerned with the development of military switching equipment. In 1954, he became chief of the newly formed Switching Branch.

G. W. Bartle

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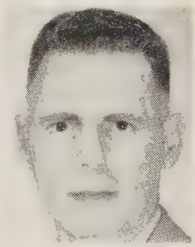
William H. Blatti was born in Woodward, Okla., on February 13, 1917. He received the B.S. degree in journalism from the University of Illinois, Urbana, in 1942. He then entered the United States Marine Corps where he served in Pacific amphibious operations from 1942 through 1945, and later in Korean combat operations from 1952 to 1953.



W. H. Blatti

From 1953 through 1957 he was assigned to Headquarters, Marine Corps, and served successively, as chief of tracked vehicle procurement and distribution, and chief, ordnance technical section for procurement, distribution and maintenance of guided missiles and ordnance materiel.

In 1957, he transferred to the United States Army Signal Corps, and until July 1, 1960 served as the Deputy Commanding Officer of the Fort Monmouth Procurement Office, U. S. Army Signal Supply Agency, the principal Signal Corps office for research and development, service test, and first-time production contracts.

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Lyle D. Bonney was born in Cripple Creek, Colo., on April 10, 1918. Since his arrival at White Sands Missile Range (then White Sands Proving Ground) N. M., in 1948, he has seen the development of the radar chain system from the van operation to the present system employing the AN/FPS-16 radars.

L. D. Bonney

He has served as Chief Engineer of the Small Missile Range Radar Site, Chief Engineer of "C" Station, and worked on the system engineering necessary for the integration of the AN/FPS-16 radar into the chain system. Presently he is serving as Chief Engineer, "C" Complex, which encompasses several radar stations supporting the south end of the range.

Mr. Bonney is a member of the American Rocket Society.

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Eberhard Both was born in Ahrweiler, Germany, on March 21, 1910. He studied at the University of Bonn, Germany, where he obtained the Ph.D. degree in 1934.

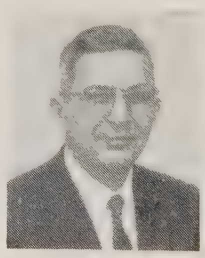
E. Both

In 1935, he accepted a position as research associate with the Vacuum Schmelze AG in Hanau, Germany, where he conducted studies of high temperature "super" alloys and of magnetic materials. From 1943 to 1947, he served as director of research for this company. He has been employed by the USASRDL, Fort Monmouth, N. J., since 1947. He initiated and directed the Signal Corps program on metallic and nonmetallic magnetic materials. In 1957, he was appointed chief of the Materials Branch, USASRDL.

Dr. Both is a member of the American Ceramic Society.

❖

Delbert A. Deisinger (A'41–SM'47) was born in Evansville, Ind., April 2, 1908. He received the B.S.E.E. degree at Evansville College, in 1931, and the M.S. degree in electrical engineering at Purdue University, West Lafayette, Ind., in 1934.



D. A. Deisinger

After working for a short time in the field of propeller design and control for the Curtiss-Wright Corporation at Buffalo, N. Y., he entered the Aircraft Radio Laboratory at Wright Field, Dayton, Ohio, in 1937, and was employed in the Transmitter Section. He later transferred to the Signal Corps Laboratory, Fort Monmouth, N. J., and entered the Radio Communications Section where he was assigned to the development of radio direction finders for military applications. In 1939 he developed the first successful VHF radio direction finder for meteorological purposes.

This instrument was a radio theodolite for tracking a transmitter carried aloft on a balloon to measure winds.

When the Radio Direction Finding Branch was organized in 1940, he became the assistant branch chief, in which capacity he continued to serve until his military service from 1942 to 1946.

He was engaged in research and development at the Signal Corps Engineering Laboratories until July, 1945, at which time he was sent to the Asiatic Pacific Theater and served in the Philippines and then in Tokyo. During the latter period he assisted in the survey of Japanese research on the ionosphere, propagation, and other geophysical areas.

After World War II, Mr. Deisinger returned to USASRDL Fort Monmouth, N. J., and continued in meteorological research and development. In 1957, with the establishment of the Meteorological Division, he was appointed director and has served in that position to the present time.

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Jules C. Domingue (A'55–M'56–SM'59) was born in Lafayette, La., on June 20, 1926. He received the B.S. degree in electrical engineering from Southwestern Louisiana Institute, Lafayette, in 1949.


J. C. Domingue

He served in the U. S. Navy from 1944 to 1946. In 1949 he began work at the USAF Electronics Training Center, Keesler Air Force Base, Biloxi, Miss., where he served as Instructor in ECM systems and heavy ground radar. In 1954 he became affiliated with USAEPG, where he worked in the development and application of tactical tropospheric systems. In 1954 he was assigned to the Army Electronic Proving Ground, Fort Huachuca, Ariz. Since that time he has also been doing graduate study at the University of Arizona, Tucson.

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Raoul A. Faralla (SM'60) was born in San Severo, Italy, on February 20, 1897. He received the B.S.E.E. and E.E. degrees in 1920 and 1930, respectively, from Cooper Union Institute of Technology, New York, N. Y.


R. A. Faralla

From 1920 to 1932, he was senior telephone engineer in the central office development department at Bell Telephone Laboratories, Inc. He was an instructor in physics in the Cooper Union Night Schools of Engineering from 1932 to 1936. In 1936, he joined what is now the USASRDL, Fort Monmouth, N. J., specializing in the design of telephones, microphones, headsets, handsets, PA systems, and recording. Since 1936, he has held various positions at USASRDL, including Chief, Microphones and Receivers Section; Chief, Acoustics Branch; Chief, Audio Equipment Branch; and Chief, Data Recording Branch. He is now a member of the Exploratory Research Communications Division, being mainly concerned with research for accomplishment of automatic, real-time, speech-to-code conversions and bandwidth compression.

Mr. Faralla is a Registered Professional Engineer in the State of New York, a Fellow of the Audio Engineering Society, and a member of the Acoustical Society of America and the American Physical Society.

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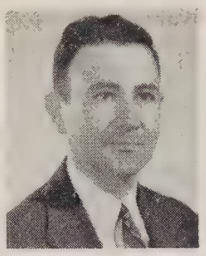
Norman J. Field was born on December 5, 1922 in New York, N. Y. He received the B.S. degree from the College of the City of New York in 1942, and the M.S. degree in physics from the Polytechnic Institute of Brooklyn, N. Y., in 1959.


N. J. Field

He joined the Signal Corps Radar Laboratory in 1942; and, except for active duty in the U. S. Army from 1944 to 1946, has held various scientific and managerial positions in the U. S. Army Signal Research and Development Laboratory in the areas of materials research, crystal physics and chemistry, and research administration. These include assignments as Chief of Optical Microscopy, Chief of External Research, assistant to the Director of Research, Director of Mathematics Division. Since 1958 he has been Assistant Director of the Institute for Exploratory Research, USASRDL, Fort Monmouth, N. J. He has also been on the teaching staff of Monmouth College, West Long Branch, N. J., since 1956.

Mr. Field is a member of the American Physical Society, the Optical Society of America, the American Chemical Society, and the American Crystallographic Association.

❖

Robert E. Frese (S'51–A'53–M'57–SM'59) was born in New York, N. Y., on March 30, 1928. He received the degrees of B.S.E. in electrical engineering and B.S.E. in mathematics in 1951, the M.S.E. degree in electrical engineering in 1952, and the Ph.D. degree in electrical engineering in 1959, all from the University of Michigan, Ann Arbor.

While in the U. S. Navy from 1945 through 1947, he completed the U. S. Navy Electronics Material Program and served with the Communications Supplementary Activity.

From 1952 through 1957 he was engaged in research at the Willow Run Laboratories of the University of Michigan in the vulnerability to countermeasures of air-terminating guided missile systems. In 1957 he joined the electrical engineering faculty of the University of Michigan as an instructor and later as an assistant professor, and continued his research work in countermeasures as a consultant. In 1959 he joined the U. S. Army Electronic Proving Ground, Fort Huachuca, Ariz. as Deputy for Scientific Affairs to the Director of Combat Developments, which includes the fields of combat surveillance, avionics, electronic warfare, electromagnetic environmental testing, automatic data processing, signal communications and meteorology. Also in 1959, he became a member of the Board of Directors of Consumers Union, Mount Vernon, N. Y., publisher of *Consumer Reports*.


R. E. Frese

Dr. Frese is a member of Phi Eta Sigma, Eta Kappa Nu, Tau Beta Pi, Phi Kappa Phi, Sigma Xi, the Arizona Computer Association and the AIEE.

❖

Lawrence G. Fobes was born in Hartwick, Iowa, on October 10, 1918. He received the B.S. degree in electrical engineering from the University of California, Berkeley, in June, 1942.


L. G. Fobes

He signed for Signal Corps service on December 6, 1941, and accepted an appointment with the Signal Corps Laboratories, Fort Monmouth, N. J. upon graduation. He has been closely associated with Army VHF and microwave radio relay development since that time. He has served as test engineer on Radio Sets AN/TRC-5 and AN/TRC-6 and as project engineer on Radio Sets AN/TRC-25, AN/TRC-26, AN/TRC-29 and AN/GRC-66.

Mr. Fobes is now chief of the Radio Relay Branch, Transmission Facilities Division, USASRDL, Fort Monmouth, N. J.

❖

Eduard A. Gerber (A'50–SM'56–F'58) was born in Fuerth, Bavaria, Germany, on April 3, 1907. He received his education at the Institute of Technology in Munich and Berlin, Germany. From the former, he received the M.S. degree in 1930, and the Ph.D. degree in 1934, both in physics.

In 1935, he joined the scientific staff of the Carl Zeiss Works, Jena, Germany, and was in charge of research and development in

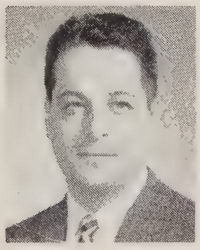
piezoelectric crystals. He arrived in the United States in 1947, and from that time until 1954, he was a consultant to the Signal Corps Engineering Laboratories, Fort Monmouth, N. J., on all matters pertaining to frequency control. Since 1954, he has been Director of the Frequency Control Division, USASRDL, at Fort Monmouth.


E. A. GERBER

Dr. Gerber is a member of the IRE Standards Committee and the IRE Committee on Piezoelectric and Ferroelectric Crystals. He has been Chairman of the latter Committee from 1958–1960.

❖

Joseph M. Giannotto was born in Newark, N. J., on May 13, 1924. He graduated from Newark College of Engineering, N. J., in 1949, with the B.S. degree in electrical engineering. During World War II he served on active duty with the U. S. Navy in the field of visual communications.

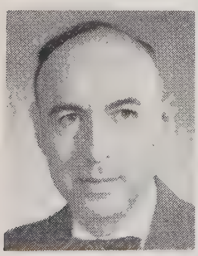

J. M. GIANNOTTO

In 1950 he joined the USASRDL, Fort Monmouth, N. J., and was engaged in development, testing and evaluation of various electronic component parts such as hook-up wire, coaxial cable, capacitors and transformers. From 1954 to 1956 he served as Chief of the Countermeasures and Detection Unit responsible for conducting electronic evaluations of short and long range radar, countermeasure and meteorological tactical equipment.

For the past four years, Mr. Giannotto has been Chief of the Tunable and Fixed Frequency Selective Devices Technical Area and has concentrated his activities on the development and improvement of electromechanical filters and RF tuning devices.

❖

Emanuel Gikow (A'48–SM'57) was born in Russia on July 1, 1917. He received the B.E.E. degree from Polytechnic Institute of Brooklyn, N. Y., in 1955.


E. GIKOW

He has been associated with USASRDL, Fort Monmouth, N. J., since 1942. During this time he has been responsible for test, evaluation and associated instrumentation of various passive electronic parts such as resistors, capacitors, dielectrics and cables. Since 1955 he has been Chief of the Inductive and Filtering Devices Section, responsible for research and development on transformers, coils, tuners, fixed and variable filters, delay lines and a variety of functionally equivalent devices such as magnetostrictive, ferroelectric and acoustic filters, delay lines and transformers.

Mr. Gikow is a licensed Professional Engineer in the state of New Jersey.

❖

William B. Glendinning (S'50–A'52–M'57) was born in West New York, N. J., on January 23, 1926. He received the B.S.E.E. degree from the Newark College of Engineering, N. J., in 1951.


W. B. GLENDINNING

From 1951 to 1954, he was engaged in development work of gaseous conduction devices at the Westinghouse Electric Corporation and the Bendix Aviation Corporation. Until 1955 he was with the Armed Services Electro Standards Agency where he was concerned with standardization work of semiconductor devices.

He joined the U. S. Army Signal Research and Development Laboratory at Fort Monmouth, N. J., in 1955, as an electronics engineer, and since then has been engaged in research and development work on solid-state devices. At present, he is enrolled at Rutgers University, New Brunswick, N. J., studying for the M.S.E.E. degree.

❖

Leonard Hatkin (A'51–M'54) was born in New York, N. Y., on March 22, 1920. He received the B.S. degree in physics, cum laude, from the College of the City of New York, in 1942, the M.S. degree in 1950 from Rutgers University, New Brunswick, N. J., and the Ph.D. degree in 1960, from the same institution.

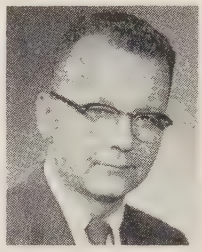

L. HATKIN

With the exception of a brief tour of active duty with the New Development Division of the War Department Special Staff during World War II, he has been with the U. S. Army Signal Corps Laboratories at Fort Monmouth, N. J., since 1942. He is currently chief of the Antenna and Microwave Circuitry Section, where he is engaged in research on and the development of VHF, UHF, and microwave antennas and their associated transmission line components.

Dr. Hatkin is a member of Phi Beta Kappa and Sigma Xi.

❖

Jerome M. Havel (A'44–M'52–SM'60) was born on February 1, 1918, in Thief River Falls, Minn. He received the B.A. degree in mathematics in 1956 from Rutgers University, New Brunswick, N. J., and, from 1956 to 1959, he did graduate work in electrical engineering at the same university.


J. M. HAVEL

Since November, 1941, he has been on the staff of USASRDL, Fort Monmouth, N. J., where he has been engaged in research and development on frequency-control devices, crystal test equipment, and frequency and time measuring techniques. In this organization, he has served as Chief of the Equipment Development Section, Chief of the Circuit Section, and Deputy Chief, Frequency-Control Branch. He is presently Deputy Director, Frequency-Control Division.

Mr. Havel has served on a number of inter-Service technical groups and coordinating committees including: Frequency-Control Devices Sub-Panel, JCEC; Test Equipment Sub-Panel, JCEC; and Test Equipment Panel, RDB. He is presently serving as Deputy Army Member, Frequency-Control Devices Working Group, AGEP.

❖

Herbert C. Hawkins was born in Fair Haven, N. J. on December 19, 1902. He was active for many years as a radio experimenter and amateur, and increased his technical knowledge by home study.


H. C. HAWKINS

Entering the government's service in the Signal Corps Laboratory at Fort Monmouth, N. J. in 1941, he shared the responsibility for the design of mobile radio communications equipment widely used in World War II. He has since been engaged in the development of radio-teletype equipment as well as military communications transmitters for both mobile and fixed station use. He was responsible for the design and construction of the ground stations for Project SCORE. He is currently Deputy Chief of the Long Range Radio Branch of USASRDL, Fort Monmouth, N. J.

Harold J. Hersh (SM'53) was born in New York, N. Y., on July 6, 1916. He received the B.S. degree in physics from Rutgers University, New Brunswick, N. J. in 1956.

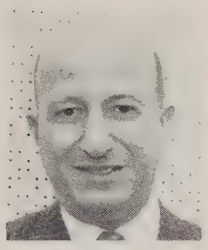
H. J. Hersh

He joined the Electron Tubes Division of the USASRDL, Fort Monmouth, N. J., in 1942, and is presently Chief of the Microwave Tubes Branch.

Mr. Hersh is a member of the Working Group on Microwave Tubes of the Advisory Group on Electron Tubes.

❖

John H. Homsy (SM'47) was born on March 15, 1907 in New York, N. Y. He attended the University of California, Berkeley, where he received the B.S. degree in electrical engineering in 1928. Following a year of employment with public utilities, he entered the federal service in 1929.



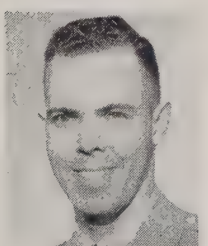
J. H. Homsy

He has been successively employed as a radio and electronic engineer by the Department of Commerce, Federal Radio Commission, Federal Communications Commission and the U. S. Army Signal Corps. He is presently Technical Director of the Electronic Environmental Test Department at the U. S. Army Electronic Proving Ground, Fort Huachuca, Ariz.

Mr. Homsy is past Chairman of both the Dallas-Fort Worth and the Fort Huachuca section, IRE. He served on several committees for the Southwestern IRE Conference, Dallas, between 1948 and 1955. He is a member of Eta Kappa Nu.

❖

Edwin T. Hunter was born in Niagara Falls, Ontario, Can., on March 28, 1933. He received the B.S. degree in chemistry from Carnegie Institute of Technology, Pittsburgh, Pa., in 1954, and was awarded the Ph.D. degree in nuclear chemistry by Columbia University, New York, N. Y., in 1959. After leaving Columbia, he entered active service with the U. S. Army Signal Corps, and was stationed at the USASRDL, Fort Monmouth, N. J., where he is now a member of the technical staff, Electronic Components Research Department, and is handling matters concerning the nuclear radiation effects program of the Department.

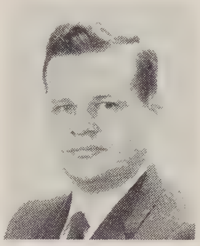


E. T. Hunter

Lieutenant Hunter is a member of the American Chemical Society and the Armed Forces Communication and Electronics Association.

❖

Edward J. Kaiser (S'54–M'57) was born in Newark, N. J., on June 14, 1929. He enlisted in the U. S. Army in 1947 and served with the Signal Corp until 1951. In 1956 he received the B.S. degree in electrical engineering from the Newark College of Engineering, Newark, N. J.



E. J. Kaiser

Since 1956, he has been employed by the USASRDL, Fort Monmouth, N. J. He is presently engaged in magnetron development work in the Microwave Tubes Branch of the Electron Tubes Division.

❖

Louis L. Kaplan was born on May 5, 1919, in Brooklyn, N. Y. He received the B.A. degree in science at Brooklyn College, N. Y., in 1937, and has attended a special course in nuclear engineering given in September, 1958 at Stevens Institute of Technology, Hoboken, N. J.

L. L. Kaplan

From 1937 to 1942 he was employed by the Continental Silver Co., Brooklyn, N. Y. as a product engineer. He has been with the USASRDL, Fort Monmouth, N. J., since 1942. He is presently the Chief of the Techniques Branch, Electron Tubes Division, and is in charge of the environmental research program on electron tubes.

Mr. Kaplan is a member of the Advisory Group on Electron Tubes, Working Group on Tube Techniques, and the Ad Hoc Committee on Mechanical Techniques. He is a long term member of the EIA-JTC 5.3 Subcommittee on Mechanical Tests. He is also a member of Sigma Xi.

❖

Edward K. Kaprelian (SM'60), was born in Union Hill, N. J. on June 20, 1913. In 1934, he received the M.E. degree from Stevens Institute of Technology, Hoboken, N. J. He studied law from 1937 to 1938, and physics, from 1943 to 1944, both at George Washington University, Washington, D. C.

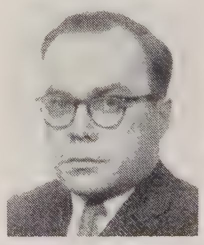
E. K. Kaprelian

He was a patent examiner in the U. S. Patent Office from 1936 to 1942, and became a physicist with the Board of Economic Warfare from 1942 to 1945. In 1946, he joined the Signal Corps Laboratories, Fort Monmouth, N. J., where he was Chief of photographic research and development until 1952. Then he became director of research and engineering for the Kalart Co. and later formed his own research and development consulting firm. In 1957, he rejoined the USASRDL, Fort Monmouth, N. J., where he is a Deputy Director of research. He holds over thirty patents in the fields of optics photography and electronics.

Mr. Kaprelian is a fellow and past President of the Society of Photographic Scientists and Engineers, a member of the Optical Society of America, the Physical Society of London, Sigma Xi, and the National Research Council—National Academy of Sciences.

❖

Francis E. Kavanagh was born in New York, N. Y., on May 24, 1929. He received the B.S. degree in physics in 1952 from Fordham University, New York. N. Y.



F. E. Kavanagh

He joined the Electron Tubes Division of the U. S. Army Signal Research Development Laboratory, Fort Monmouth, N. J., in 1952. He is presently a member of the Microwave Tubes Branch, where he is engaged in the development of klystrons and traveling wave tubes.

❖

Kenneth K. Kelly was born on December 3, 1923 in Pittsburgh, Pa. He is a graduate of the Air Force Navigation School, Selman Field, La., and has four years experience as an Aerial Navigator and Navigation Instructor. In addition he attended the University of Pittsburgh, Pa., and Monmouth College, Long Branch, N. J., and received the B.S. degree in physics from the latter in June, 1960.

K. K. Kelly

He was the Signal Corps Project Engineer for Doppler Navigation Systems and

was associated with the Avionics Division of USASRDL, Fort Monmouth, N. J., from 1955 to July, 1960. He is now employed by the Laboratory for Electronics, Inc., Boston, Mass., as the New York regional marketing manager.

❖

K. G. LEISTNER

K. G. Leistner was born in Germany, on April 20, 1901. He received his undergraduate degree in 1924 and the Ph.D. degree in 1931, both from the Institute for Photographic Research, Technical University, Dresden, Germany.

After teaching photography at a professional school, he joined the photographic department of Carl Zeiss, Jena, Germany, in 1929, working on performance evaluation of lenses and photographic systems as well as on production of high precision reticles by photographic methods. At the end of the War, he and other Zeiss specialists moved with the American Army to South Germany and assisted in laying the groundwork for the new Zeiss plant at Oberkochen. In 1947, he accepted a position in the Photographic Branch of the USASRDL, Fort Monmouth, N. J., where he is now a consultant and chief of the Photo Research Section.

Dr. Leistner is a member of the Optical Society of America, the Society of Photographic Scientists and Engineers, and Sigma Xi.

❖

D. LINDEN

David Linden was born in New York, N. Y. on January 26, 1923. He received the B.S. degree in chemistry from the College of the City of New York, in 1942 and the M.S. degree in chemistry from the Brooklyn Polytechnic Institute in Brooklyn, N. Y., in 1950.

He joined the USASRDL Fort Monmouth, N. J., in 1942. In 1956, he became the Deputy Director of the Power Sources Division at the USASRDL, a post which he still holds.

❖

M. A. LIPTON

Milton A. Lipton was born in New York, N. Y., on May 1, 1917. He received the B.E.E. degree in 1939 and the E.E. degree in 1946 from Cooper Union Institute of Technology, New York, N. Y.

He is the Chief of the Data Equipment Branch of USASRDL, Fort Monmouth, N. J. He has been responsible for engineering programs at that laboratory for the last twenty years in the areas of communication cable development; communication system developments for guided missile, special weapon, and air defense projects; and presently, automatic data processing families of equipments. He is credited with the design of the standard army field communication wires and cables, and holds several patents for communication devices. He represents the Department of the Army on several industrial and scientific committees.

Mr. Lipton is a member of the AIEE and a fellow of the AAAS.

❖

A. L. LONG, JR.

Alton L. Long, Jr., was born on September 25, 1932, in Liberty, Texas. He received the B.S. degree in chemistry from Carnegie Institute of Technology, Pittsburgh, Pa. in 1953. He served there as a research chemist on an AEC project, then returned to full-time graduate study, receiving the M. S. degree in nuclear chemistry in 1955.

As an officer in the U. S. Army he was stationed at Fort Monmouth, N. J. for two years, serving as a project officer and participating in nuclear weapons tests. He remained at USASRDL as a civilian engaged in the study of radiation effects on electronic components. He is currently engaged in similar work for the Burroughs Corporation, Great Valley Laboratories, Paoli, Pa.

Mr. Long is a member of the American Chemical Society and the American Nuclear Society.

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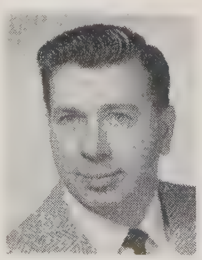

W. W. MALINOFSKY

Walter W. Malinofsky was born in Perth Amboy, N. J., on December 6, 1924. He received the B.S. degree in physics in 1951 from Rutgers University, New Brunswick, N. J., and is undertaking graduate work at the Polytechnic Institute of Brooklyn, N. Y.

Since 1951 he has been associated with the USASRDL, Fort Monmouth, N. J., where he has been the author of several papers. At present he is a supervisory physicist (solid-state) in the Materials Branch of the Electronic Components Research Department. He has engaged primarily in research in solid state physics, X-ray crystallography, ferromagnetism and ferroelectricity. He is currently in charge of the development of new magnetic materials in the field of radio frequency communications.

Mr. Malinofsky is a member of the American Physical Society and the American Crystallographic Association.

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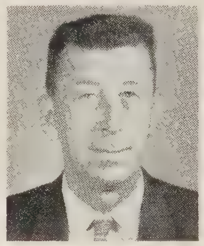


R. L. NORTON

Richard L. Norton was born in Dover, N. H., September 8, 1913. He received his degree from the University of New Hampshire, Durham, in 1935.

He is active in the Army Reserve and has the reserve rank of Colonel. His last military assignment was as an instructor at Fort Bliss, Tex. In 1959, he joined the Missile Electronic Warfare Division of the U. S. Army Signal Missile Support Agency, White Sands Missile Range, N. M., after completing fifteen years of military service. He is presently a project engineer with the Missile Electronic Warfare Division and is responsible for the design and fabrication of the Dynamic Target and Countermeasures Simulator and also for the vulnerability evaluation of the REDEYE missle.

❖

H. A. NYE

Herbert A. Nye was born in Sharon, Pa., on June 19, 1914. He received the B.A. degree from Allegheny College, Meadville, Pa., in 1936, and the M.S. and Ph.D. degrees from the University of Illinois, Urbana, in 1938 and 1941, respectively.

He was a graduate teaching assistant at the University of Illinois from 1936–1941. He taught undergraduate and graduate physics at the University of Illinois from 1941 to 1946, and at the University of Buffalo, N. Y., from 1946 to 1953.

In 1953, he joined the Cornell Aeronautical Laboratory, Buffalo, N. Y., as a principal physicist. He is now Director of the Cornell Aeronatucial Laboratory Combat Surveillance Project.

Dr. Nye is a member of the American Physical Society, the American Ordnance Association, and Sigma Xi.

❖

Irving R. Obenchain, Jr., (SM'51) was born in Birmingham, Ala., on May 23, 1921. He received the B.S. degree in general

engineering from the U. S. Military Academy, West Point, N. Y., in 1942, and the M.S. degree in electrical engineering from Massachusetts Institute of Technology, Cambridge, Mass., in 1951. He attended the Industrial College of the Armed Forces in 1958.

I. R. Obenchain

During the last ten years, he has been assigned to the Signal Laboratory, the Signal Agency at the White Sands Proving Ground, and the Office of the Chief Signal Officer, Washington, D. C. Prior to joining the Signal Laboratory in September, 1959, he served on the general staff as chief of the Operations Division G-4 (Logistics) Section of the Eighth Army in Korea. He is presently chief of the Technical Staff, USASRDL, Fort Monmouth, N. J.

Colonel Obenchain is a member of Sigma Xi.

❖

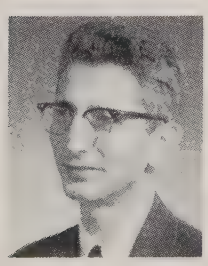
Theodore A. Pfeiffer, Jr. was born in Newark, N. J., in February, 1925, His engineering studies at the Newark College of Engineering, N. J., were interrupted with two and a half years of service in the U. S. Army. He received the B.S.E.E. degree in 1949.

T. A. Pfeiffer

Upon graduation, he joined USASRDL, Fort Monmouth, N. J. His work at the Laboratory has included the planning and direction of manual and automatic switching systems development. At present, he is Deputy Branch Chief of the Switching Branch, Communications Department.

❖

Abraham Rand was born in New York, N. Y., on July 21, 1907. He studied at New York University School of Engineering and Rutgers University extension at Fort Monmouth, N. J.

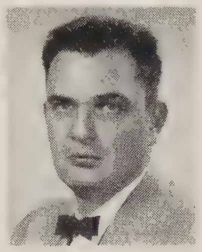


A. Rand

In 1942 he joined the USASRDL in Fort Monmouth, where he was initially engaged in the development of FM voice communication circuitry. Since 1945 his activities have become more specialized in the inductive component field covering pulse, power and audio transformers. More particularly, as project engineer or advisor, he conducted research and development projects concerning corona in power and pulse transformers and optimum design criteria for pulse and broad-band RF networks. Within the past few years he has been engaged in "solid-type" inductive devices using, largely, ferroelectric ceramics.

❖

Bernard Reich (M'57) was born on January 7, 1926 in New York, N. Y. He received the B.S. degree in physics from the College of the City of New York, N. Y., in 1948. From 1948 to 1954, he did graduate work in electrical engineering and mathematics at Rutgers University, New Brunswick, N. J., attending on a part-time basis.



B. Reich

He joined the USASRDL, Fort Monmouth, N. J. in 1948. From 1948 to 1954, he served as radiation physicist, and was Radiological Safety Officer from 1951 to 1953. From 1955 to 1958, he was chief of the Device Engineering Section, Solid State Devices Branch. Since 1958, he has been chief of the Circuit Functions Branch, Solid State Devices Division, Electronic Components Research Department.

❖

Irving Reingold (SM'58) was born in Newark, N. J., on November 13, 1921. He received the B.S. degree in engineering in 1942 and the Engineers degree in 1949, both from the Newark College of Engineering Newark, N. J. He has done graduate work in electronics at the Brooklyn Polytechnic Institute, N. Y., and is a licensed Professional Engineer in the state of New Jersey.

I. Reingold

From 1943 to 1945 he was an electronics manufacturing engineer in the Electron Tube Section of the Westinghouse Electric Company, Bloomfield, N. J. From 1945 to 1951 he was a project engineer in the Radar Branch of the Watson Laboratories, Air Materiel Command, Red Bank, N. J. In 1951 he joined the Electron Tubes Division of the USASRDL, Fort Monmouth, N. J., and is presently chief of the Switching Devices Section of the Microwave Tubes Branch.

Mr. Reingold is serving on IRE Task Group 7.3.1, Measurement Methods for the TR and ATR Tubes, and IRE Subcommittee 28.6, Magnetic Devices. He also serves as the Department of the Army Deputy Member of the Working Group on Microwave Tubes, Advisory Group on Electron Tubes. He is the holder of several patents.

George F. Senn (SM'50) was born on May 11, 1913 in Philadelphia, Pa. He received the B.X.E.E. degree from Drexel Institute of Technology, Philadelphia, in 1935.

G. F. Senn

In 1935 he was with Philco Radio and Television Company in Philadelphia and in 1936 with Radio Corporation of America in Camden, N. J. In 1937, he joined the UASARDL, Fort Monmouth, N. J., and since that time has been chief of the Vehicular Installation Section, chief of the Quality Control Division, and is currently the chief engineer of the Communications Department. In 1958, he was the project manager in charge of the "SCORE" Communications Satellite Project.

❖

John Shwop (M'59) was born on September 16, 1919 in Philadelphia, Pa. He received the B.S. degree in chemical engineering from Drexel Institute of Technology, Philadelphia, Pa. in 1942.

J. Shwop

Since 1942 he has been employed by the Signal Corps. From 1942 to 1950 he was engaged in quality assurance engineering. During the years 1950–1953 he was chief of the Philadelphia Quality Assurance Division. From 1953 to 1955 he worked as materials engineer in the Production Development Division of the industrial preparedness activity. He was an electronic engineer in the field of semiconductor devices from 1955 to 1958. Since then he has been chief of the Engineering Branch "C," concerned with vacuum and solid-state electronic devices, Production Development Division, U. S. Army Signal Supply Agency, Philadelphia, Pa.

❖

Pierce W. Siglin was born in Hazelton, Pa., on November 26, 1913. He has attended Rutgers University, New Brunswick, N. J.

P. W. Siglin

Since 1942 he has been employed by the USASRDL, Fort Monmouth, N. J., working in the areas of guided missile test range instrumentation, electronic mapping and survey, marine, air, and ground navigation, and satellite communications. He is presently Deputy Chief, Astro Communications Branch, USASRDL, and Program Manager on Project Courier.

Mr. Siglin has served on various technical committees including the Navigation Technical Group, Research and Development Board, Army Observer TACAN Steering Group, and is presently a member of the Communication Committee, American Rocket Society.

Joseph M. Stanley was born in Boston, Mass., on August 30, 1911. He received the B.S. degree in chemical engineering from Northeastern University, Boston, Mass., in June, 1935.

J. M. Stanley

From 1936 to 1940, he was an Industrial Engineer with the United Drug Company in Boston. He entered Government service in 1940 as an engineer at the U. S. Armory, Springfield, Mass. While there, he was actively engaged in various chemical and metallurgical studies associated with ordnance research and development. In 1942, he joined USASRDL, Fort Monmouth, N. J., where he has been responsible for conducting research investigations into the synthesis of crystals for Signal Corps applications, particularly those concerned with frequency control. He is currently employed as a supervisory physicist with responsibility for directing quartz crystal research investigations.

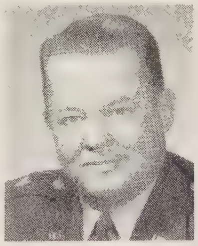
Mr. Stanley is a member of the American Chemical Society.

Samuel Stiber was born in New York, N. Y., on March 31, 1909. He received the B.S. and M.S. degrees from the College of the City of New York, in 1931 and 1933, respectively.

S. Stiber

From 1935 to 1940, he was an instructor in physics and mathematics in Puerto Rico. Returning to the United States in 1941, he became an instructor in radio engineering at the Air Force Technical Training Command, Scott Field, Ill. From 1943 to the present, he has been a radio engineer at the Evans Signal Laboratories, Belmar, N. J. In the U. S. Army Signal Corps for approximately seventeen years, he has been involved in electronic-warfare research and development programs, concerned particularly with electronic reconnaissance, radio direction finding, and signal analysis and recording functions. His present position is that of chief of the Detection and Location Branch, Countermeasures Division, Surveillance Department, USASRDL, Fort Monmouth, N.J.

William M. Thames was born in Roanoke, Va., on October 18, 1907. He received the B.S. degree in electrical engineering at Clemson A&M College, S. C., in 1932.



W. M. Thames

He was called to active duty in February, 1941, and was assigned as Post Signal Officer at Camp Blanding, Fla. During World War II, he served in Alaska and then in Europe. Following the war, he became assistant director of engineering at the Signal Corps Engineering Laboratories, Fort Monmouth, N. J. He was then assigned as Commanding Officer of the Signal Corps Plant Engineering Agency, Philadelphia, Pa. Following a tour as student at the Command and General Staff College, Fort Leavenworth, Kans., he was transferred to Japan as Deputy Signal Officer of the Far East Command, in which capacity he served during the Korean hostilities. He since has attended the Army War College, Carlisle Barracks, Pa., has been assigned to the office of the Chief Signal Officer, Washington, D. C., and completed the Advanced Management Course given at Fort Belvoir, Va. He was then assigned as Deputy Commander of the U. S. Army Electronic Proving Ground, Fort Huachuca, Ariz., where he served until he became Commanding General of U. S. Army Combat Surveillance Agency, Arlington, Va.

General Thames is a member of Tau Beta Pi.

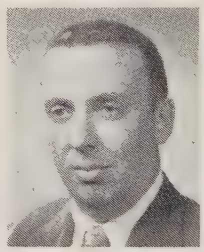
Arthur L. Vieweger (A'39–SM'53) was born in Estelville, N. J. on May 2, 1904. He received the B.S.E.E. degree from the University of Pennsylvania, Philadelphia, in 1927 and the M.S.E.E. degree from Massachusetts Institute of Technology, Cambridge in 1929.

A. L. Vieweger

While attending M.I.T., he was a student engineer with the General Electric Company in Lynn, Mass. He then worked as telephone engineer for 4 years with the Bell Telephone Company of Pa. and the American Telephone & Telegraph Company. He was then a radio engineer with Philco Radio & Television Corporation, leaving that position to join the Signal Corps Laboratories at Fort Monmouth, N. J., in 1937. At the Signal Corps Laboratories, he first worked on the development of the early radar receivers and oscilloscopes used in experimental work and the service tests of SCR-268 and SCR-270. He then developed the Range Unit and Keyer used an SCR-268-T-1, and subsequently the Keying and Modulating portions of SCR-268 and SCR-270. He next was placed in charge first of the production engineering of these radars and when the Signal Corps Radar Laboratory was formed, the production engineering of all the Signal Corps radars.

He served as 1st Lieutenant, Captain and Major during the war, first at the Signal Corps Laboratories, and then, in 1944, upon graduating from Command and General Staff College, Fort Leavenworth, Kans., in Europe. In the European Theater of Operations, he served as Chief Engineer (Radio), Psychological Warfare Division, SHAEF. In late 1945 he resumed civilian status at the Signal Corps Laboratories and has occupied various positions associated with Radar and Guided Missile Electronics since that time. He served as Deputy Member, Panel on Radar, Research and Development Board. He is presently Assistant for Engineering and Development to the Director, Surveillance Department, USASRDL, Fort Monmouth, N. J.

Sherman B. Weiner was born in Rochester, N. Y., on July 31, 1922. He graduated from the University of Michigan, Ann Arbor, in 1947, with the B.S.E.E. degree.



S. B. Weiner

Later that year, he joined the Stromberg-Carlson Company, a Division of General Dynamics, Rochester, N. Y., as an electrical engineer. He is presently manager of the Advanced Development Branch of the Telecommunications Engineering Department of the Telecommunications Division.

Klaus Westermann was born in Munich, Germany, on October 1, 1924. He received the Dipl. Ing. degree in electrical engineering at the Technische Hochschule, Munich, in 1950.

K. Westermann

From 1950 to 1957 he was an engineer in research and development of microwave communication systems in the Communication Division of the Telefunken Company in West Germany. In

1957 he came to the United Srates, joining the Electron Tubes Division of USASRDL, Fort Monmouth, N. J. He is presently engaged in the development of klystrons, traveling-wave tubes, and backward-wave oscillators.

Albert S. White, Jr., was born in Worcester, Mass., on November 23, 1911. He received the B.S.E.E. and M.S.E.E. degrees from Worcester Polytechnic Institute in 1933 and 1934, respectively.

A. S. White, Jr.

He has been continuously associated with the development of military radar equipment since 1938, from 1945 to 1951 with the Watson Laboratories of the Air Force, and the remaining time with the USASRDL, Fort Monmouth, N. J., where he is currently Deputy Director of the Radar Division.

Robert F. Wilson was born in Altoona, Pa., on July 11, 1905. He received the B.S. degree in industrial engineering from Pennsylvania State University, University Park, in 1928. After graduation, he was associated with the Penn Central Light and Power Company, as a valuation engineer.

R. F. Wilson

As a reserve officer, he was called to active duty with the Signal Corps in 1941. For the past nineteen years his duties have mainly been in the Procurement and Distribution Service of the U. S. Army Signal Corps. He served as the Commanding Officer of the Fort Monmouth Procurement Office of the U. S. Army Signal Supply Agency until September 1, 1960. His office was responsible for the placement and administration of research and development, and service test contracts for the Signal Corps in the fields of communications, radar, surveillance, electrical and electronic components.

Harold A. Zahl (A'39–SM'46–F'50), for a photograph and biography, please see p. 390 of the April–July, 1960 issue of these Transactions.

Hans K. Ziegler, for a photograph and biography please see page 62 of the April–July, 1960 issue of these Transactions.

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ON

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